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Iterative Generation of Synthetic Power System Networks for Load Flow Studies

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fulfillment of the requirements for the degree of Master of Engineering.

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Abstract

Today, there is only a small number of generally available power system test networks, and often their sizes are not considered sufficient. These networks are necessary to test the performance of various computational algorithms used for a variety of power system analysis applications. Besides the need to have generally available power system test networks with parameters that closely match those of realistic power systems, the continuously increasing sizes of practical power systems also dictates a growing requirement for larger and larger test networks.

A new method is proposed for the development of artificial, but reasonably realistic, power system networks of arbitrary size and complexity, suitable for full load-flow analysis (having feasible load-flow solution). It is based on an iterative procedure to expand an initial network by adding a new bus and/or line at each iterative step, until the system of the desired size and complexity is reached. The method is implemented using a new "backwards" approach, which maintains the network determined in the previous iterative step the same everywhere, except at the bus (or buses) where the new network element is added. This new approach ensures that, without any upgrade of the initial system, the newly expanded network will satisfy all the system constraints typically required in realistic power system networks, and that it will have a feasible load-flow solution. The size and complexity of the final output network are specified and controlled by the user. Furthermore, the proposed method provides the potential to interconnect one or more previously developed systems into even larger test power grids, which also resemble realistic power systems and have feasible load-flow solutions.

Five different sample networks, together with all the data necessary for full load-flow calculations have been computed to illustrate the performance of the new method. Their sizes range from a 66-bus / 86-line, to a 330-bus / 430-line network. The topological complexities requirements vary from moderate to relatively high. In

addition, a sample 82-bus / 121-line system, generated through the interconnection of two, previously developed networks, is illustrated. All the presented networks satisfy the main requirements for load-flow test systems; they possess feasible load-flow solutions and relatively realistic network parameters. Moreover, it is noteworthy that the power flow solutions exist even when certain variations in the initial power demands (for which the network was originally designed), are introduced. Finally, these generated power systems can be used directly as load-flow test networks, or upgraded for applications in other power system studies.

Résumé

De nos jours, un petit nombre de grand réseaux électriques dédiés à des tests sont généralement disponibles. Le plus souvent, leurs dimensions sont considérées comme insuffisantes. Ces réseaux sont nécessaires pour tester les performances de divers algorithmes utilisés dans des gammes variées d'applications pour d'analyse des systèmes de puissance. Au-delà du besoin d'avoir des réseaux de test de systèmes de puissance disponibles et dont les paramètres concordent avec ceux des réseaux réels, l'accroissement perpétuel des dimensions des systèmes de puissance pratiques dicte également une demande grandissante pour des réseaux de test de plus grandes dimensions.

Une nouvelle méthode est proposée pour le développement de réseaux de systèmes de puissance artificiels mais raisonnablement réalistes et dont les dimensions et les complexités sont arbitraires. Ces réseaux sont appropriés pour les analyses d'écoulement de puissance (avec des résolutions d'écoulement de puissance réalisables). La technique est basée sur une procédure itérative pour étendre un réseau initial en ajoutant à chaque étape de l'itération un nœud et/ou une ligne jusqu'à l'obtention du système qui répond à la dimension et la complexité désirées. La méthode est mise en œuvre en utilisant une nouvelle approche dite 'rétrograde' qui maintient le réseau donné inchangé partout sauf au nœud (ou aux nœuds) où l'élément nouveau est rajouté. Cette approche nouvelle assure le fait que sans mettre à jour le système initial, le nouveau réseau déployé va satisfaire toutes les contraintes typiquement requises dans les réseaux des systèmes de puissance. L'approche garantie aussi la réalisation d'une solution pour l'écoulement de puissance. La dimension et la complexité du réseau final sont spécifiées et contrôlées par l'utilisateur. En plus, la méthode offre un potentiel pour interconnecter un ou plusieurs systèmes dans des grilles de tests de réseaux de plus grandes dimensions. Ces derniers ressemblent à des systèmes de puissance réels et ont des solutions d'écoulement de puissance réalisables.

Cinq exemples de réseaux, y compris toutes les données requises pour effectuer des études d'écoulements de puissance ont été calculés pour illustrer la performance de la nouvelle méthode. Leurs dimensions varient de réseaux de 66 nœuds et 86 lignes à d'autres de 330 nœuds et 430 lignes. Les exigences de complexité topologique varient de modéré à relativement élevé. De plus, un exemple de système de 82 nœuds et 121 lignes, généré à partir d'une interconnexion de deux réseaux déployés d'avance est illustré. Tous les réseaux présentés satisfont aux exigences des tests pour l'écoulement de puissance; Ils ont des solutions aux écoulements de puissance réalisables et des paramètres de réseau relativement réalistes. Mieux encore, il est remarquable que les solutions à l'écoulement de puissance persistent même avec des variations des demandes en puissance initiales (demandes pour lesquelles le réseau est conçu à l'origine). Finalement, ces systèmes de puissance générés peuvent être utilisés directement en tant que réseaux de test d'écoulement de puissance ou mis à jour pour des applications dans d'autres études relatives aux systèmes de puissance.

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Chapter 1

Introduction

" ... One afternoon toward sunset he and Szigety were walking in the city park, and Tesla was reciting Goethe's 'Faust'...

Then, "the idea came like a flash of lightning, and in an instant the truth was revealed".

Tesla's long, waving arms froze in midair as if he had been seized by a fit. Szigety, alarmed, tried to lead him to a bench, but Tesla would not sit until he had found a stick. Then, he began to draw a diagram in the dust.

"See my motor here; watch me reverse it", he exclaimed.

The diagram then he drew would be shown six years later in his address before the American Institute of Electrical Engineers, introducing to the world a new scientific principle of stunning simplicity and utility. The application of it would literally revolutionize the technical world.

It was an entire new system that he had conceived, not just a new motor, for Tesla had hit upon the principle of the rotating magnetic field produced by two or more alternating currents out of step with each other.

... there had been no truly successful AC motor until Tesla invented his - an induction motor that was the heart of a new system and a quantum jump ahead of his time."

" Tesla: Man Out of Time" , Margaret Cheney

Tesla's new induction motor and its various modifications, such as for polyphase induction and the polyphase synchronous motor, together with previous patents for the AC transformer, have formed the basis for the modern utilization of electric power.

Today, we are so used to the presence of this "miracle" which excited people only a hundred years ago, when the first electric public street lights were introduced in New York city, that most of us rarely even think of the power which affects our lives in so many ways - from replacing the use of candle light, to operating most of the essential equipment in hospitals and airports. Yet, despite its importance, hardly anyone will consider what is behind a switch when we turn on a light, or inside an outlet box when we plug in a heater, a radio or a computer... The whole "behind the scenes" system, a grid which resembles a masterpiece "spider web", usually remains known only to the "electrical" people, who are concerned not only with how to deliver electric energy to our homes and plants, but also how to maintain the quality of that supply as well. Only when the supply is interrupted, or when the whole system collapses, do we realize how much our lives are dependent upon the use of electric energy, and how important a role this supply plays in our lives. The task of operating power systems reliably and economically, while respecting their increasing demands and size, remains as a primary challenge to power system electrical engineers, and not only in traditionally operated vertically integrated power systems, but even more in the new "world" of operation under competition and open transmission access.

Electric power is produced in power plants. At the heart of each power plant is a three-phase synchronous generator which consists of a stator and a rotor. A DC current flowing through the winding on the rotor, induces an AC current in the stator windings, due to a time-varying magnetic field set up by the rotor motion. For a constant rotor velocity, the sinusoidal voltages generated in each of the stator windings are identical in frequency and magnitude, but separated by 120° in phase.

An external force is needed to move the rotor of the generator. The power of water flow is used in hydroelectric power plants, while in thermal and nuclear power plants hot steam plays the role of prime mover. The design and construction of generators can vary, depending on the required speed of rotation, but the main principle of the three-phase synchronous generator - the induction of current in the stator due to the rotation of the magnetic field set up by the rotor's current - remains the same.¹

Electric power is transferred from power plants to the substations, and further, to the points of consumption, along overhead or underground transmission lines and distribution feeders. Throughout this process, it is not only important to transfer sufficient energy from the power plants to the consumers, but also to maintain the quality of the supply within prescribed limits, such as predetermined voltage and frequency ranges. Therefore, power system networks consist of nodes - or *buses* - connected together by transmission lines. In general, the voltage levels of the lines can vary, and transformers are used to step the voltages up or down to the required levels. A generator and/or load can be connected to each node, and the overall generation must meet the load demands (including losses and reserves) at all instants in time. Also, in order to maintain the voltage levels within the given constraints, specialized compensating devices may be connected at certain buses. Their task is to improve operating conditions along the lines from the voltage profile point of view.

An alternative to AC transmission is *high-voltage direct current* (HVDC) power transfer, which is suitable for long distance overhead or underground lines. DC power lines are less expensive, have fewer losses and are capable of delivering more power per conductor than equivalent AC power lines. The primary disadvantage of HVDC is that AC/DC converters are needed at both ends of the line, which increases the cost of its operation (but not for significantly longer distance transfers). A practical

¹Apart from the generation in power plants, relatively recently some sources, such as solar, wind, wave, geothermal, tidal and nuclear fusion have been investigated. Their application is still very expensive, and they are regarded mostly as "auxiliary" sources in remote areas, or used to reduce the consumption of electric energy from the power system network.

network of DC lines is not yet possible because protection and switching equipment is not as good as that available for AC transmission. So, even though DC transmission has some advantages over AC transmission, its usage remains very limited, and it is only appropriate for transferring power over long distances and in some special circumstances such as cables below the sea.²

The operation of a power system should be reliable, able to withstand some external disturbances and accommodate certain changes in power demands without discontinuity of the supply, or violations of constraints on voltage and frequency limits. In order to enable such operation, or to improve existing operating conditions, different power system studies are routinely performed using various computational algorithms. To test the performance of competing algorithms it is necessary to compare the results obtained using a new method with the solutions of previously established methodologies. Of course, such comparisons are easiest and most valid if the investigations are done on the same examples, i.e. the same networks. This is the main reason why having generally available power system networks is an important issue in this area of computational power systems research.

Today, there is a small number of IEEE test networks available to the researcher, but neither their number nor their sizes are considered sufficient. The aim of this thesis is to develop an approach for the generation of artificial, but reasonably realistic, power system networks of arbitrary size and complexity. The proposed method consists of two main parts. First, a core network of a specified number of nodes and configuration is determined. Then, starting from such a given core network, the algorithm adds new nodes and/or lines, one by one, to expand the system up to the required size and connectivity. By design, the parameters of the existing network are not altered throughout the expansion process. The power-flow solution for the previous and the enlarged network remains unchanged, except for the power

²An example of such DC transmission is used under the English Channel between Great Britain and France, and under the Baltic sea, between Sweden and island of Gotland.

demand (and/or possibly supply) associated with the bus where a new node is added. Similarly, the addition of a new line offsets only the power demands and/or supply at the nodes local to that connection. Therefore, the overall change in power conditions from the first to the second network is accommodated by the modification of power demands (and/or generation) at the affected buses only.

Moreover, two or more of these networks can be connected together into a larger system through the addition of *tie-lines* between selected buses. Again, these connections yield system alternations only at the tie-line starting and ending points, and the associated power changes are balanced locally, so that there is no difference in the power flows along the lines for each of the initially separate networks before and after an interconnection.

1.1 Network Layouts

The purpose of a power system network is to connect the locations of the generating plants with the electrical load centers, and transmit the energy to points of demand. Frequently, the best geographical locations for generating facilities do not coincide with the major region demands. As a result, there is a need either to transport the electric energy from power plants built near the natural energy sources, or to transport the fuel from the sources to the power plants that are built near the consumer centers. The first solution demands the existence of a power network, while the second might be considered for fossil-fuel plants, but is not feasible for hydro-plants. In reality, the solution is usually something in between, since power system design is not dependent only on the location of natural sources and load demands, but on other technical, economical and environmental constraints as well.

Generally, the aim of every power system utility is to supply the power reliably, with the least possible interruption of service, and with a specified quality, which is

described by voltage magnitude and frequency values and the limits between which they are constrained. The economical operation of the system is also an important factor that should be taken into consideration.

Due to rapid changes in electric power consumption on one hand, and increased demands for improving continuity of service and economy of operation on the other hand, most systems are electrically interconnected into vast power grids which are subdivided into regional operating groups - *power pools*. Even though power systems are connected, they have their own internal structures, which may vary from one system to another, and operate quite independently, each having its own policy. In order to maintain electrical connectivity and exploit certain generation and regulation advantages of a pool, these systems are typically tied to each other through tie-lines which permit the transfer of energy between systems in both directions.

Recently, certain modifications in the operation of vertically integrated power systems, which usually incorporate both the generation and transmission parts of the system, were investigated. The new policy proposed a disintegration of generation and transmission portion of utilities, in order to encourage more competition among generators, and reduce the price of energy. Yet, even under the deregulated operation, the reliability and quality of supply are to be maintained by an Independent System Operator (ISO).

The structure of a power system is mainly determined by its size and the geographical locations of demand and source points. Also, the configuration of each network can be affected by the topology of the regions through which its circuits pass, and will reflect the philosophies and policies applied in the past. Whatever system arrangement is used, it is important to ensure enough flexibility to cover all likely network problems and leave some room for future, yet presently unknown, development and growth. Ideally, all this should be accomplished at a minimal cost.

The operating voltage levels increase with the electric energy transmission de-

mands and distances over which it must be transferred. Consequently, the voltage levels of the transmission lines are closely related to their energy transmission capacities. Voltage levels increase with the level of power transfer, and today's extra high voltage transmission lines are the direct results of increases in power consumption that occurred in previous periods.

According to voltage level and electrical connection, the structure of a typical power system can be vertically partitioned, as shown in Figure 1.1 [2], into the following transmission levels:

1. transmission and pool level
2. subtransmission level
3. distribution level

The transmission levels associated with the subtransmission and distribution networks typically form one power system. A number of such power systems can be connected together through tie-lines into a power pool.

Transmission level

The transmission level is the highest in a power system, and it is distinctly different from both the subtransmission and distribution systems. The line voltages range from 115 kV to as high as 765 kV with line ratings from 100 MVA to over 4000 MVA [3]. Transmission level systems transfer the largest amount of energy, and interconnect most of the generation units and major load demand points of the system.

Normally, transmission networks are designed so that large blocks of power can be transferred over a number of alternative routes, and so that the loss of one or a few lines will not seriously disable the system. Apart from increasing the reliability

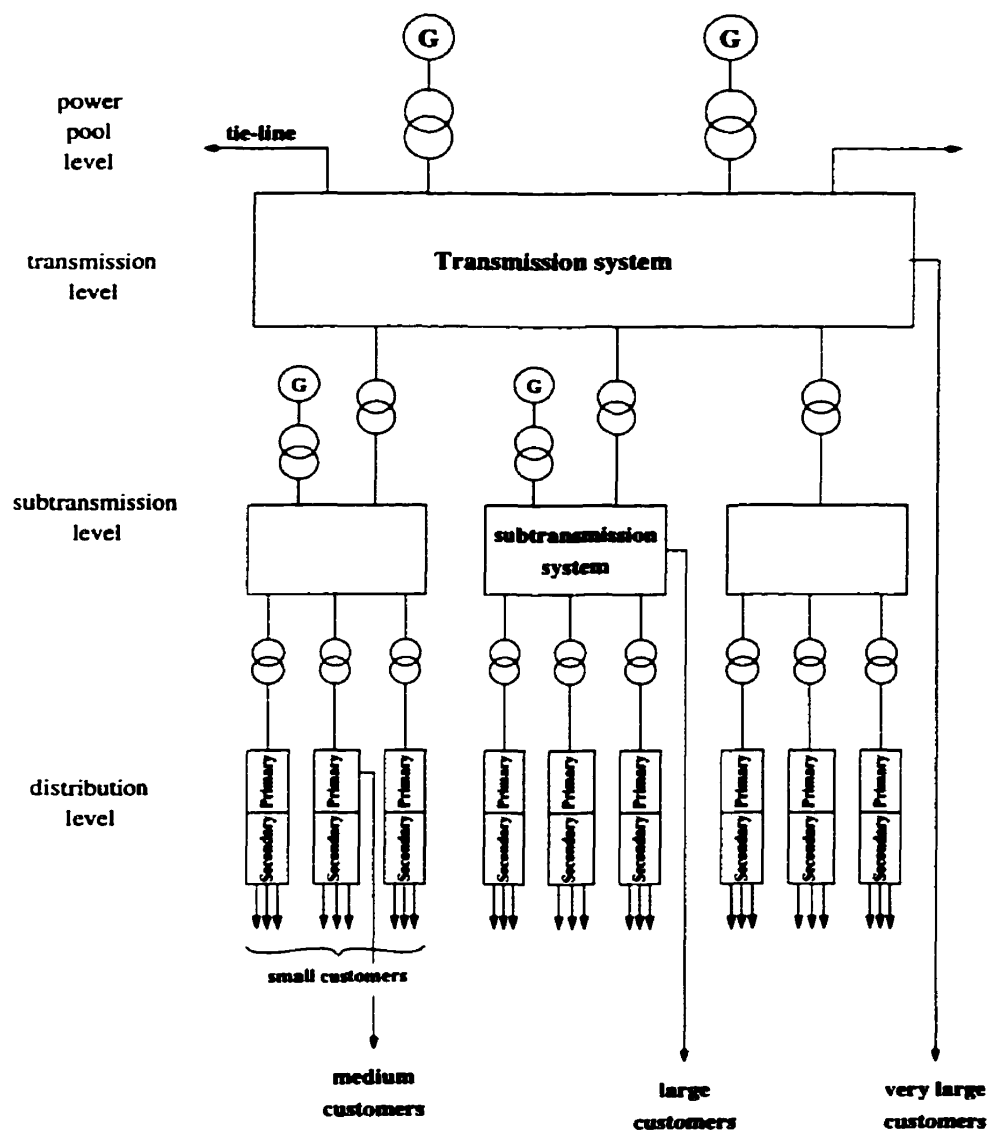


Figure 1.1: Structure of the vertically integrated power system.

of the supply, the possibility of routing power transfers over different paths also allows for improved economical operation and regulation of the power system.

An interconnection of two or more power systems into a power pool is done at the transmission level through tie-lines, so transmission systems govern power exchanges and supply assistance among interconnected grids.

Subtransmission level

The main role of the subtransmission level is to distribute the energy from the transmission level to the distribution systems. Voltage levels of this intermediate system range from 23 kV to 138 kV. Typically, individual subtransmission circuits are fed from a single bus - *a bulk power station*, or a generator bus in a generation station. They generally deliver power to distribution substations in surrounding geographical regions.

In many cases, subtransmission systems functioned as transmission levels in the past. However, due to increased demands and overall transmission, such grids have been frequently upgraded over time by overlaying transmission lines with higher capacities. With such upgrades in voltage levels, an old transmission network can change the role it played in the system, and become a new subtransmission portion of the grid.

Distribution level

The distribution level represents the lowest level of a power system, and corresponds to the most detailed “mesh” of the system. It distributes the energy from the subtransmission substations to the medium-sized (small industrial and commercial) and small (domestic) customers. (The larger demand loads, as illustrated in Figure 1.1, are usually connected directly to the higher voltage levels of the power system.) In comparison with transmission and subtransmission networks, smaller

blocks of power are transferred through distribution lines, and usually over shorter distances. Two voltage levels can be distinguished in distribution networks:

1. The *primary* or *feeder* voltage levels (for instance 23 kV), which consist of individual circuits that extend from the substations to the consumers' locations, where final voltage step-down transformation is done.
2. The *secondary* or *consumer* voltage levels (i.e. 120/240 V), which operate on the lines from the final transformation point to the customers themselves.

Primary systems usually have a predominant radial or loop structure, while the secondary depends on the load density of the area. In the center of large cities, where the average load density can exceed $100\text{MW}/\text{km}^2$ [4], secondary distribution systems often form a rather complicated, strong underground cable grid-type network. For rural areas with small load densities, radial arrangements are usually more suitable.

1.1.1 Network Structures

As mentioned earlier, there is difference between the transmission level on one side, and subtransmission and distribution systems on the other side, due to the distinct functions of these systems. As a result, generally, the network structures of these systems can be different. The transmission system usually forms a mesh or a loop structure, while the other two systems generally have a radial structure, although in heavy load regions, such as city core areas, a highly meshed distribution network is often present. However, these are only tendencies, which can vary widely according to the particular needs of the consumers, the pre-existing power grid and the constraints of the environment.

- **radial structures** are usually encountered at the subtransmission and distribution levels. It is a good solution in the cases where the flow of power has a predominant direction. The typical form of a radial network structure is shown in Figure 1.2.

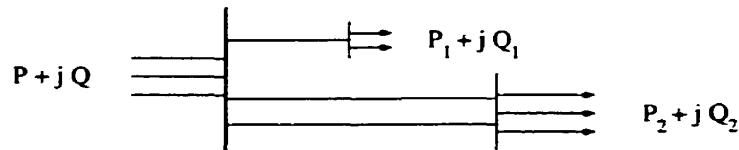


Figure 1.2: Radial network.

The pure radial structure is mainly used for the supply of rural areas, in which small to medium-load densities are present. Also, in North America it is often used at distribution level. One variation of the radial structure incorporates a radial supply with alternate paths (Figure 1.3 [5]), which is usually used at subtransmission levels, and sometimes applied in the case of a distribution supply. This type of system operates as radial, but in the case of a failure along one path, the alternate route can support the transmission of all the required power. Thus, in the case of a line failure the network topology may be changed and the power may flow through the alternate paths. These alternate subtransmission circuits may be on the same right of way, but are not necessarily so.

- **backbone structures** are often used at the transmission level, as illustrated in Figure 1.4. Generators and loads are placed along strong transmission lines that stretch throughout the system. It might be regarded as a hybrid type between pure radial and a loop system, and it is mainly used in areas with specific geographical locations of sources and major demands, like in Quebec, Canada.

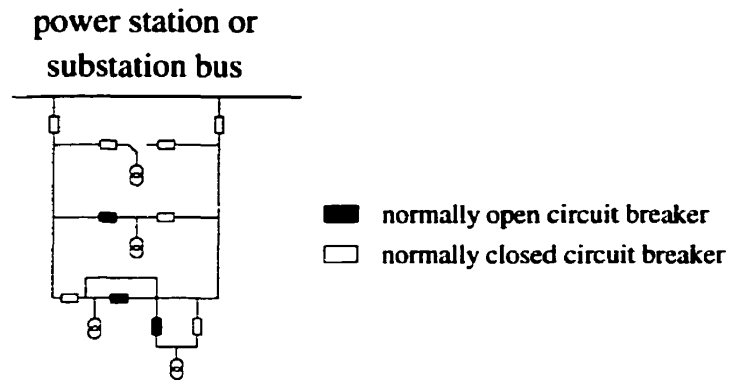


Figure 1.3: Radial supply with alternate paths.

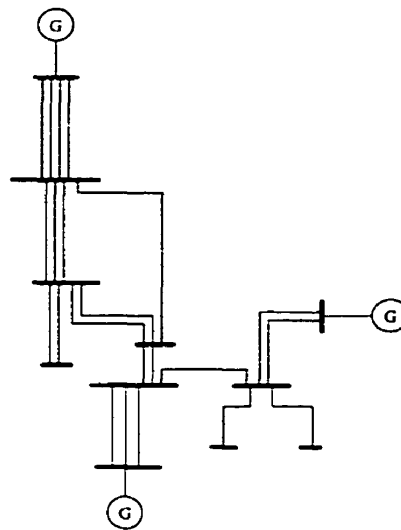


Figure 1.4: Backbone structure.

- **mesh structures** are mainly used at the transmission level (Figure 1.5), since they provide better continuity of supply in cases of outages. This arrangement is usually more efficient in terms of total current costs, although it requires more substation equipment and more sophisticated protection. Since mesh structures increase the reliability of the supply, they can also be used at the subtransmission level (Figure 1.6), where lower level voltage interconnections are prevalent. In some cases, loop structures are applied in distribution systems as well. They

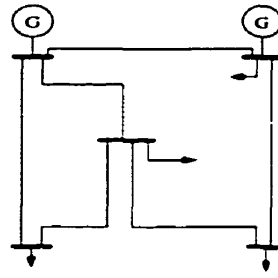


Figure 1.5: Mesh (or loop) network.

are used in areas with medium and, especially, heavy load densities (e.g. city core areas), to improve the reliability and/or the voltage quality along the lines.

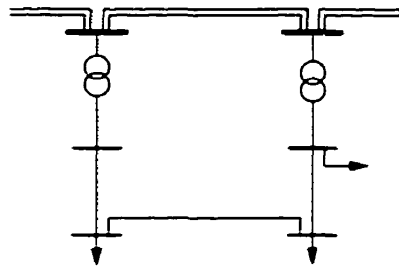


Figure 1.6: Interconnection at lower voltage.

- **ring or belt structure** networks are described by Figure 1.7. Typically, the lines are interconnected into a ring or, sometimes, into a double ring.

Here there is less connectivity between the nodes than in mesh networks, but the reliability of the supply is still considerably higher than in a radial arrangement, because an alternative path exists in the case of a line failure.

A number of flat rural areas tend to be interconnected using this type of configuration. Also, it is typically used for transmission systems that supply large cities (like in Hamburg, Germany and Paris, France) when high voltage transmission lines come to the edges of the cities and enter substations in the suburbs. From there, the subtransmission system takes over further distribution.

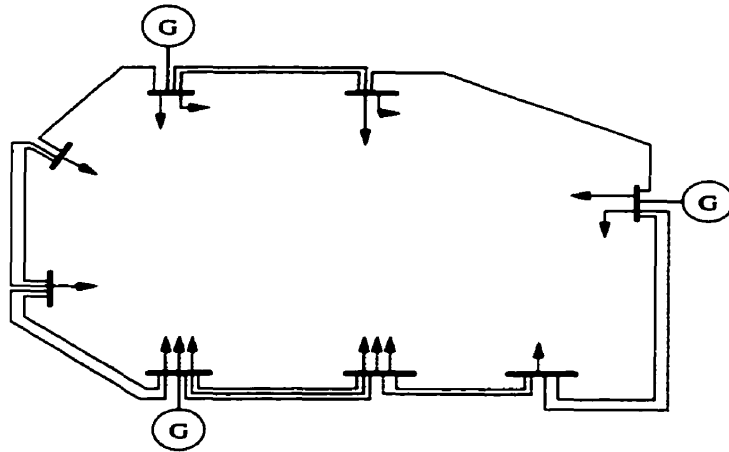


Figure 1.7: Ring network structure.

In practical applications, power systems are usually made up of a combination of different network structures and voltage levels, since they generally involve a wide variety of topological features and load densities.

1.2 Types of Power System Analysis and Applied Techniques

In order to investigate the phenomena which occur in power systems, and to predict and control their behavior either in normal or alert operation, it is necessary to describe the physical characteristics of the power systems by appropriate mathematical models. First, each element of the system is represented by an equivalent circuit that can simulate its behavior according to the particular analysis under consideration. These models are appropriate mathematical representations of physical elements and they introduce acceptable approximation error levels which depend on

their complexity and precision.³ Then, the behavior of the system itself may be modeled by a set of equations. Due to the typical sizes of power system networks, it is usually necessary to solve large systems of algebraic and/or differential equations (nonlinear or linear). Normally, various numerical methods are used, which may also introduce a certain amount of error into the solution. This error does not depend directly on the error introduced by mathematical modeling, but rather on the behavior of the chosen numerical method.

Sometimes, when the computational time is quite long (which can often happen in the case of large networks) and a great number of similar calculations are to be repeated, the overall computational effort can become much too expensive. In this case, certain simplifications may be introduced, especially if the initial data are only known to within a limited accuracy.⁴

Generally, there are a number of main types of analysis that are usually performed to evaluate and adjust power system operation. One of the most basic is the *power-flow problem*. It solves the power system network for steady-state operation, and yields information about the voltages and the power injections at each bus. Power flows along the lines can be readily calculated, once the power-flow variables and parameters are known. The power flow equations and the models used for the power system elements are described in detail in Chapter 2, since this type of analysis is at the heart of the methodology for assembling artificial networks proposed in this thesis.

Another important aspect of power system operation is its response to possible disturbances that can occur due to sudden changes in the network topology (like the opening of lines) or in the power balances, or caused by faults (which actually produce

³If less accurate results are needed certain parameters might be neglected, introducing corresponding levels of error. For example, a resistance or shunt capacitance of a line can sometimes be neglected to yield a simplified model. However, for more accurate results a more precise representation should be applied and these values should be taken into consideration.

⁴For example, a simplified dc load-flow will usually be sufficient to investigate possible expansion routes in the first stage of planning.

a most violent impact). As previously mentioned, a large number of generators can be interconnected together into a power system, and they all have to operate synchronously. Under such conditions the differences between voltage phase angles are very small. A sudden failure can change (and increase) these angle differences. It is of vital importance to restore stable operation and to not allow the system to switch to an unstable mode, when large angle differences lead to big voltage differences. If the system “runs away”, these substantial voltage differences can produce large currents which, if not disconnected from the system promptly, may lead to further “cascade” failures and, eventually, even to the total collapse of the system (i.e. “black out”). Therefore, relays and current breakers must react if one of the generators loses its synchronism with the rest of the network, in order to remove it from the system as soon as possible. *Stability calculations and analysis* deal with this problem of investigating a network’s response to certain perturbations, and its ability to maintain the synchronous operation of all the interconnected generators.

A line failure can be caused by accidents such as lightning or a breakage in one or more phases or circuits along the transmission path, which leads mostly to short-circuits and high current flows. It is very important to isolate the faulted portion of the network and prevent the disturbance from spreading throughout the entire grid. Power-flow solutions of the prefaulted steady-state operation, together with results from *short-circuit analysis*, are used for the purpose of establishing proper settings for protection devices. The main duty of these devices is to react at the right moment and isolate the affected lines, in order to enable the rest of the system to continue with its operation. Ratings of circuit breakers are also chosen according to the magnitudes of fault currents. The current that is interrupted by a breaker a short time after the occurrence of the fault is high and is obtained from short-circuit calculations.

Also, *contingency analysis* investigates how the failure of a certain element will influence the operation of the network. It evaluates whether, for the possible outage (of a generator or a line) the network can still be operated safely and effectively.

Hence, it allows for the control of the network behavior and the prediction of operation so that no single contingency will cause overloads or voltages outside a given range. The effects of load changes, generation rescheduling and outages of certain elements can be obtained from the load-flow solution.

A failure of one or more elements will change the regime in the system. Usually, power grids are designed in such a way that a loss of one element does not interrupt the supply of demands. However, the failure of more elements can affect the fulfillment of the power supply, and *reliability studies* are performed to evaluate the probability that the system will deliver enough energy to the loads. Typically, these studies are done taking into consideration different influences such as weather conditions, maintenance, change in load, etc. A broad bibliographical review on the application of probability methods in power system reliability evaluation is presented in [6], [7] and [8].

Finally, the overall operation of the system should not be only safe, reliable and within prescribed quality limits, but economical as well. Different studies such as *optimal power flow*, *economic dispatching* and *unit commitment* are focused on the economic issues. Since power systems commonly involve different generators, the distribution of generation among them can be assigned in different ways. All generators do not operate at the same cost, so the expense of generating a given amount of power is not necessarily the same for each generator. Also, supplying a load from one location can be associated with different losses along the lines than if it is supplied from another generator. Economic dispatching investigates the problem of determining generation distribution so that line losses and/or generation costs are minimized. The unit commitment problem involves optimizing the generators' scheduling for some period of time, based on economic dispatching and taking into consideration fluctuations in load demands due to the change in season or time of day, and the technical features and constraints of the available generators. The overall demands and required reserve are intended to be supplied by operating the best

combination of generating units available at the time. Because of the large amount of energy and the high costs that are associated with the operation of a power system, even a small reduction of 1-2% can mean a substantial saving. An extensive survey of publications on optimal power flow and economic dispatching, with a classification of the methods, is given by Huneault and Galiana in [9], and by Chowdhury and Rahman in [10].

The power system analysis techniques and procedures summarized above are not only applied to vertically integrated power systems, they are also essential for maintaining power system operations in deregulated environment.

1.3 Power System Test Networks

To evaluate the performance of new power system algorithms extensive testing and comparisons with the results of previously adopted techniques have to be done. For objective comparisons it is highly desirable to compare solutions for the same set of initial data.

The present “state of the art” does not include either a large variety of existing test networks or suitable algorithms for the synthesis of artificial, but relatively realistic, power systems. The limited set of generally available IEEE test networks are becoming increasingly insufficient for the numerical testing of new large scale power system analysis algorithms. Also, the currently available test networks were often designed for a specific area of study, even though they may contain sufficient data for some other purposes. They can be classified into the groups described below. Very often, in the absence of more generally available and appropriate test networks, researchers try to obtain data from utilities for their real, existing systems. The problem is however, that these data are not generally accessible to other researchers.

There are a few IEEE standard test systems for load-flow studies - of 14, 30,

57 and 118 buses [1]. The outlined data include line data, operating conditions at each bus, regulated bus data with transformer and static capacitor data. All the given parameters are sufficient for testing full load-flow methods. These systems are well known and often used. The 57 bus system is illustrated in Figure 1.8.

Another group of test data consists of networks for reliability studies. The IEEE Reliability Test System (IEEE RTS) prepared by the IEEE Reliability Test System Task Force [11] has been primarily designed for reliability analysis, but also has sufficient data for load flow testing. The system contains 24 buses and 38 lines. It describes a load model, generation system and transmission network, giving the basic data for reliability evaluations such as daily, weekly and seasonal patterns of load and different outage rates for generating units, transmission lines and transformers.

Even though the IEEE RTS system provided a generally acceptable set of data both for generation capacity and composite system reliability evaluation, experience has shown that some limitations existed. In 1986, an extension to this system was introduced by Allan et al. in [12]. It addressed the problem of the limitation associated with the generating portion of the system and provided additional data for derated states and maintenance of the generating units, together with the effects of interconnections and load forecast uncertainty.

Aside from the IEEE RTS, the basic data for a reliability test system for educational purposes was presented in [13] by Billinton et al. It was designed for the development of the basic concepts in reliability studies, and therefore it is smaller in size (6 buses and 11 transmission lines). The basic system data necessary for adequacy evaluation at the levels of generation and composite generation and transmission, as well as data for cost/reliability worth evaluation are given. Also, in 1991, an addition to the reliability test system for educational purposes was introduced by Allan et al. [14], to extend the existing network with data for a distribution part of the network.

Apart from the above-mentioned IEEE test networks, some smaller systems

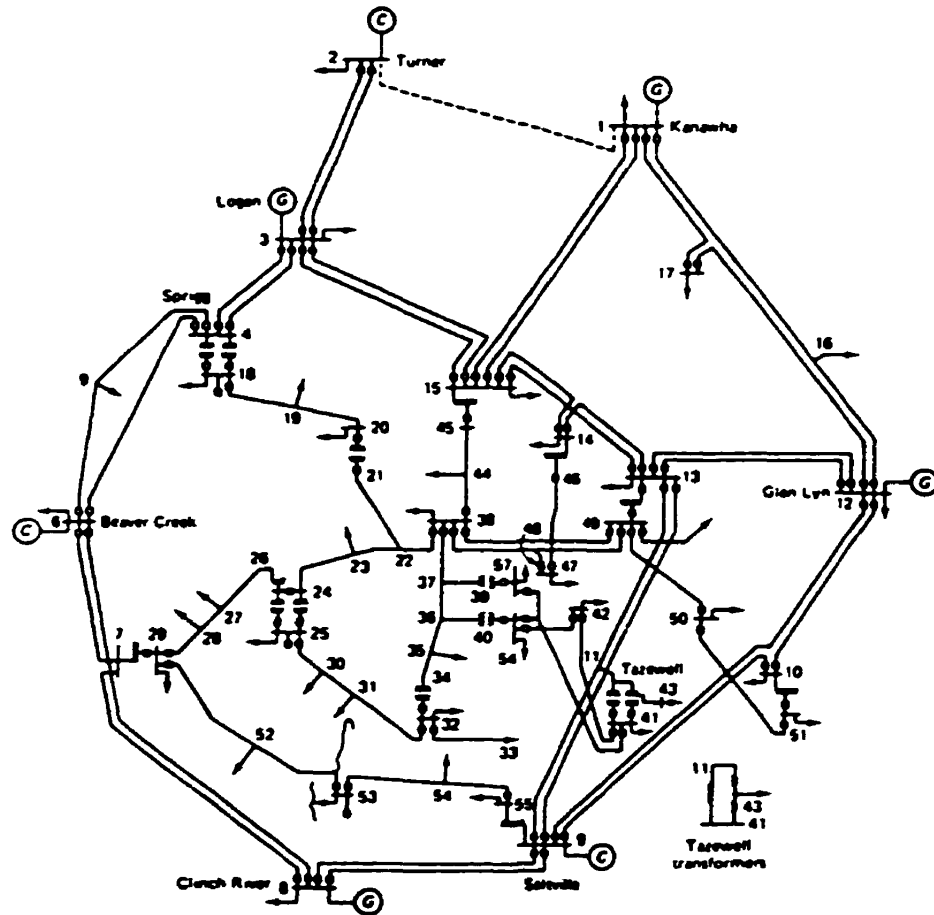


Figure 1.8: IEEE 57 bus test system [1].

were proposed by CIGRÉ. They were part of an exercise prepared for discussion and comparison of applied techniques for particular analyses such as optimization of power system operation [15], and reactive compensation for a long distance transmission system [16].

Common to all the above-mentioned articles is that they provide systems and necessary data for a specific area of a research. So, the aim was not to show how their data were obtained, nor to give an indication of how similar networks could be produced. The test networks are simply presented “as is”, without any discussion on the merits, or of the studies that led to the adopted values and topology. The dominating subject was the specific study for which the network was designed, and not the method for assembling the network itself. Therefore, in our study of synthesizing artificial power system networks all the above-mentioned references could be used only as an indication of which data would be needed for a certain research area and within which limits their values should fall, but not as a guideline on how to construct such networks.

Simulation of power systems is another area which seems interesting for the examination of the power systems networks used for system representation. Simulators are intended to serve for investigating the behavior of the system under certain conditions as either batch studies, or in real-time applications, when used for testing the behavior of equipment and when training dispatchers to operate systems under both normal and disturbed conditions (in the same manner as airplane pilots are trained on flight simulators) [17]. Generally, simulators are not intended for network generation, rather they use previously defined sets of data. Moreover, dispatchers are typically trained to operate one specific system, so the adopted “training” network need only to resemble the one they will manage on the job, and there is no need to equip one simulator with a variety of different and randomly assembled networks. Therefore, the types of power systems studies, and techniques and models of representation applied in power system simulators, give a very good and detailed picture

of the data required for a test network, but do not answer the question of how the adopted power systems are obtained.

The lack of test networks, or the lack of available data from the utilities for the general public, can be overcome by introducing synthetically generated data. This type of problem exists in some other fields, such as finite element electromagnetic analysis, where it is a common practice to generate and use artificially synthesized data for benchmark comparison studies. However, the problem of generating such data for power system analysis is not frequently met in the literature, even though it is a topic whose results would be of value to many researchers in the area. One approach to this problem is given by Javidi, McFee and Galiana in [18]. Their algorithm can generate systems of arbitrary size and complexity, and the resulting networks may be composed of one or a number of local blocks. The single block networks may have two different topologies - a star and a grid type, while multi-block networks are composed of a number of sparse interconnected blocks. The line parameters and nodal voltages are randomly chosen from within a certain range, while injected real and reactive powers are calculated at all buses. Also, certain control actions are applied to ensure good convergence of a designed network for a load-flow solution. Thus, the values assigned to the network elements and system configuration can be controlled by the user.

The algorithm developed in this thesis gives another possible approach to the generation of artificial load-flow test networks of arbitrary size and connectivity, which possesses the features associated with real power grids. The proposed method has two parts. In the first part a core network is assembled. The shape of the initial grid and the number of nodes are specified by the user, while the power demands and generation points are chosen randomly; the required transmission lines are determined accordingly. Then, starting from the core network, further expansion is accomplished by adding one node after another, or a new line between existing nodes, until the desired network configuration and size is attained. The first and second parts of the

program are decoupled, allowing the user to intercede and alter voltage conditions in the core system by adding compensating devices at certain buses.

Throughout the expansion process, a network determined in the previous step will not change anywhere but at the bus (or buses) where a new element is added. Power flows along the lines in these two networks stay the same, except in the new, added line. The power delivered to the new node, or a power flow in a new line connected between previously existing buses, is accommodated by a modification of power demands and/or possibly generation at the points of connection. However, the “equivalent” power demand (“seen” by the rest of the system) at these nodes, as well as overall injected power in all others, does not change. This means that it is not necessary to check the entire network for additional corrections when a new element is added, because there will be no impact on any other part of the system. Everything previously determined in the system will operate in the same manner and with the same values, except the load, and possibly generators or Static Var Compensators (SVCs) at the points of connection. Variations in the active and reactive powers of these elements (or an addition of any of them, if needed) will be sufficient to maintain the very same operation in the rest of the system. So, if the system operates satisfactorily before an expansion, the new element will not produce an instability (unless the proposed addition is not feasible).

In addition to this network expansion procedure, new networks of larger sizes can be obtained by interconnecting previously developed systems through one or more “tie-lines”. Such combinations can be constructed in numerous ways, allowing a user to quickly assemble different large grids, using previously defined ones, no matter whether they were the results of earlier expansions or previously implemented tie-line interconnections. So, each new network can be added to a “library” of existing systems and then reused either “solo”, or as a building block in the process of assembling new interconnections.

1.4 Thesis Outline

Since the objective of this thesis is to propose an algorithm for the development of artificial load-flow test networks, the load-flow problem and the network models implemented in this type of analysis are presented in Chapter 2. Also, the simplified approaches to power flow studies are outlined as a basis for the discussion of the possible approaches to the problem of iterative network expansion. These potential methods for the incorporation of new network elements into a previously developed system are outlined in Chapter 3, and compared with the newly proposed “backwards” technique. The detailed description of the implemented “backwards” algorithm is presented in Chapter 4, while the output test networks are discussed in Chapter 5, together with the possibilities for future work. The potential of the proposed algorithm is illustrated with five developed power systems. These sample test networks are presented in Appendix A. For each network the topology layout is given together with the set of line and bus data, as well as the corresponding load-flow solution.

Chapter 2

Load Flow Analysis and Network Models

A load-flow analysis determines the power flows along each line in a power system network, and is considered to be one of the most fundamental approaches for investigating power system operation in a steady-state regime. For the given network topology and parameters, a load-flow solution specifies four variables at each bus - *active power P , reactive power Q , voltage magnitude V and voltage phase angle δ* - which can be used to calculate the power flows, and fully describe the state of the system. The power injections and the voltage at each bus, as well as the network parameters, are sufficient to calculate the required power flows.

Power flow analyses are important for the management of power systems operating under normal steady-state conditions, as well as for the study of failures, optimal system operation, and in planning studies of power system upgrading. The load-flow problem has been a focus of interest for many years because it forms the basis for a wide range of power system studies. Solving large networks at high computational speed, sometimes even in real time for on-line applications, is a common concern in modern power system analysis. Therefore, a substantial amount of time and effort has been invested in developing new algorithms and improving established methodologies. This interest and research has resulted in numerous contributions

offering a variety of approaches to power flow analysis, and has helped to establish the study of power flows as a well-known and well-defined research area [19].

A power system network under study is described by its topology, line parameters, transformers and compensating devices, together with the active power generation and load demands at each bus. An important part of any power system study is to establish adequate models for both the system network elements and the phenomena under study. Each element of the power system is modeled to respect and represent the physical aspects that are of importance in the particular analysis. The behavior of the system itself is also modeled by equivalent equations that reflect the physical characteristics of the studied phenomena. Equations that model system behavior for load-flow studies are based on Kirchhoff's laws, which for a general full load-flow problem form a system of nonlinear algebraic equations requiring an iterative method of solution. Since steady-state operation in a sinusoidal regime is of interest, fast transient phenomena (and the parameters associated with them) are neglected, and differential equations are not introduced. Currents, voltages, powers and impedances are expressed as complex variables [17]. Also, it is assumed that the system operates in a balanced state, so that only single-phase positive-sequence equivalent circuit representations are needed. Moreover, in load-flow analysis, only elements such as lines, transformers, generators, loads and compensating devices are modeled, while the switching equipment is not generally of interest (and therefore its impact is neglected).

2.1 Network Modeling

The first step in any power system analysis, including load-flow studies, is to represent the elements of the given power system network by appropriate electrical models. The accuracy of the adopted models and the approximations introduced to

reduce their complexity will usually depend on the methodologies used to solve the particular problem, and the required accuracy of the solution. For simplified algorithms that are usually applied when fast methods are needed, or when values of certain variables can be only estimated, less accurate (and less complicated) models may be sufficient. More complex models, that take into account parameters that might otherwise be neglected, are usually only useful in studies that require high accuracy of the solution and use more accurate algorithms. Also, single-phase equivalent circuits are sufficient, since a balanced steady-state operation of the system is assumed. For the purpose of power flow studies, the most commonly adopted models for transmission lines and transformers are two-port linear circuits with lumped parameters ([2], [3], [20], [21]).

2.1.1 Transmission Lines and Cables

A transmission line, or a cable connecting two nodes i and k , is usually modeled by an equivalent π -circuit as illustrated in Figure 2.1, where the series impedance $\underline{Z}$ is defined as

$$\underline{Z} = R + jX = R + j\omega L \quad (2.1)$$

and the shunt admittance $\underline{Y}$ is

$$\underline{Y} = G + jB \approx jB = \frac{j\omega C}{2} \quad (2.2)$$

In matrix form, the equations for the equivalent π model are:

$$\begin{bmatrix} \underline{I}_S \\ \underline{I}_R \end{bmatrix} = \begin{bmatrix} \frac{jB}{2} + \frac{1}{R+jX} & -\frac{1}{R+jX} \\ -\frac{1}{R+jX} & \frac{jB}{2} + \frac{1}{R+jX} \end{bmatrix} \begin{bmatrix} \underline{V}_S \\ \underline{V}_R \end{bmatrix} \quad (2.3)$$

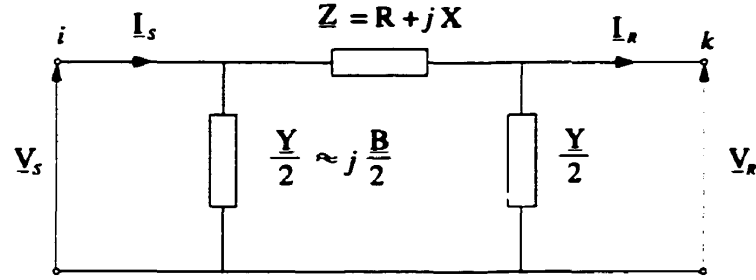


Figure 2.1: Equivalent π -circuit of a line.

In this model, the resistance R , inductance L , capacitance C and shunt conductance G are treated as lumped parameters. Even though all four parameters of a transmission line are uniformly distributed along the line, in reality application of the equivalent π -circuit with lumped parameters is more suitable for computational purposes and yields sufficient accuracy - especially in the case of short and medium length lines. Moreover, in real power system networks the shunt conductance G can usually be neglected (as indicated in equation (2.2)), so the admittance $\underline{Y}$ only takes into consideration the capacitance to the neutral of the line, and half of its value is lumped at each end of the equivalent circuit [22].

Generally, transmission lines can be divided in three categories according to their length. Short lines are considered those that are less than 80 km long. Often for their representation even a simpler circuit than the equivalent π can be adopted, because the influence of the shunt capacitance of short lines is often neglected, and only R and L are usually considered. Medium-length lines range between 80 km and 250 km. They are modeled well by the equivalent π -circuit provided in Figure 2.1. Lines longer than 250 km are considered as “long-lines”. For their representation, correction factors that account for the difference between the nominal π -circuit with lumped parameters and the fact that the parameters of the line should really be uniformly distributed along the line can be introduced. This correction is not always needed, and is usually only introduced in cases when greater modeling accuracy is desired.

Normally in load-flow analysis, the line parameters required for representing transmission lines and cables are defined on a per unit length basis:

$\underline{z}$ - series impedance per unit length ($\underline{z} = r + jx$)

$\underline{y}$ - shunt admittance per unit length ($\underline{y} = g + jb$)

l - length of the line

Therefore, the total lumped parameters of the π -circuit become:

$$\underline{Z} = \underline{z} l = rl + jxl = R + jX \quad (2.4)$$

$$\underline{Y} = \underline{y} l = gl + jbl = G + jB \quad (2.5)$$

2.1.2 Transformers

Transformers play an important role in power system networks by enabling values of transmission voltages to be substantially higher than the values that can be produced by synchronous generators. Also, they serve to isolate generators from the rest of the power grid, so that overvoltages that may occur within the network due to failures can not reach the synchronous generator and cause damage.

Various types of transformers are in general use, and they may differ in size and type of winding connections, depending on their role and location in the system. Generally, large transmission transformers used in transmission and subtransmission networks can be classified in three categories [2]:

1. *Generator Transformers* - devices that step-up generator output voltage levels to the transmission voltage levels.
2. *Transmission Transformers* - devices that transform power between different voltage levels in the transmission power system.

3. *Regulating Transformers* - devices that are capable of tap changing under load (TCUL), and are used for controlling the power flow by changing the voltage at a certain point of the system. The amount of change ΔV is usually small, and in general, both the phase and magnitude of the voltage can be changed, in order to control the flow of the real and reactive power respectively.

Transformers are also modeled by two-port equivalent circuits. The classical representation of a transformer is often given as an equivalent Γ -circuit, but in order to maintain compatibility with the transmission line models equivalent π -circuit representations are usually adopted.

Transformers on Nominal Ratio

A non-ideal transformer with turns ratio t can be modeled by an equivalent circuit which consists of an ideal transformer in cascade with an equivalent π -circuit whose leakage impedance and magnetising impedance are obtained using the standard short-circuit and open-circuit tests. Typically, for most analyses, a per-unit system is adopted, so that that turns ratio t for a transformer on a nominal tap ratio becomes $t = 1$. In this case the ideal transformer may be omitted, leading to the equivalent circuit illustrated in Figure 2.2.

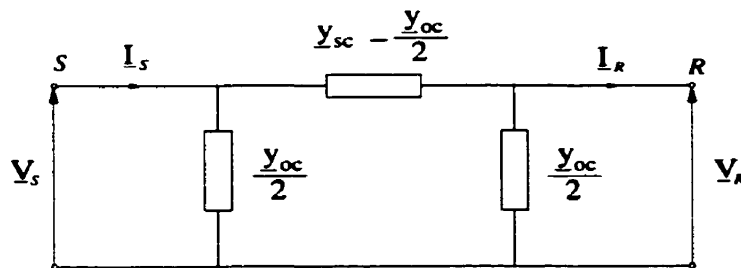


Figure 2.2: Equivalent π -circuit of a transformer.

Moreover, in power flow studies, this equivalent circuit is often further reduced to a single lumped impedance (or only reactance, if the resistance of the transformer is neglected) between the primary and secondary busbars (Figure 2.3), with the following matrix representation:

$$\begin{bmatrix} \underline{I}_S \\ \underline{I}_R \end{bmatrix} = \begin{bmatrix} \frac{1}{jx} & -\frac{1}{jx} \\ -\frac{1}{jx} & \frac{1}{jx} \end{bmatrix} \begin{bmatrix} \underline{V}_S \\ \underline{V}_R \end{bmatrix} \quad (2.6)$$

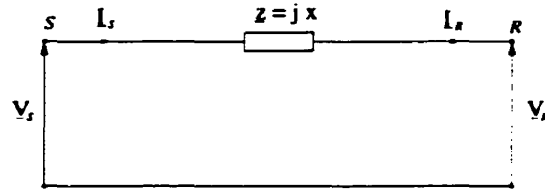


Figure 2.3: Simplified equivalent circuit of a transformer.

Transformers on Off-nominal Ratio

When a transformer is set for off-nominal ratio, the turns ratio is $t \neq 1$ (in per-unit). In this case, it can be represented by an ideal transformer in cascade with the admittance jx as shown in Figure 2.4 (a). For real values of turns ratio t , its π -equivalent circuit (with neglected resistance) is given in Figure 2.4 (b).

The relationships between the voltages and currents are:

$$\frac{\underline{V}_S}{\underline{V}_T} = \frac{1}{t} \quad \frac{\underline{I}_S}{\underline{I}_T} = t \quad (2.7)$$

Also, from Figure 2.4 (a):

$$\underline{V}_S = \frac{\underline{V}_T}{t} = \frac{\underline{I}_T}{t y} + \frac{\underline{V}_R}{t} \quad (2.8)$$

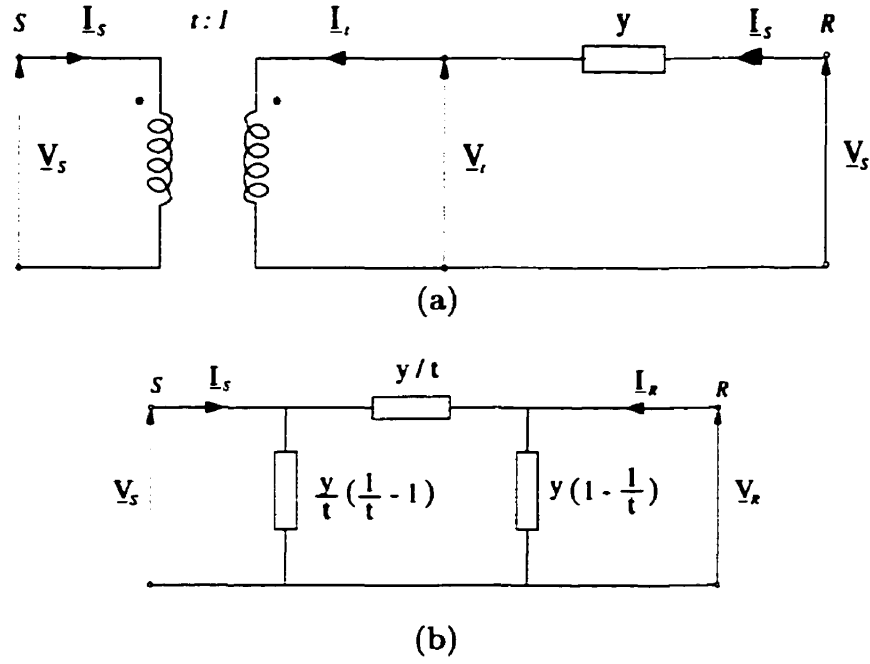


Figure 2.4: Equivalent circuits of the transformer on off-nominal ratio.

Therefore, the corresponding set of equations in matrix form is:

$$\begin{bmatrix} \underline{I}_S \\ \underline{I}_R \end{bmatrix} = y \begin{bmatrix} \frac{1}{\underline{t}^2} & -\frac{1}{\underline{t}} \\ -\frac{1}{\underline{t}} & 1 \end{bmatrix} \begin{bmatrix} \underline{V}_S \\ \underline{V}_R \end{bmatrix} \quad (2.9)$$

A complex turns ratio $\underline{t}$ enables phase-shifting in the power system for the control of power flows. Here, two different turns ratios - one for current and one for voltage - have to be distinguished, because of the invariance of power ($\underline{S} = \underline{V} \underline{I}^*$). These two complex conjugate turns ratios are defined as:

$$\underline{t}_v = \underline{t} = e^{j\phi} \quad \underline{t}_i = \underline{t}^* = e^{-j\phi} \quad (2.10)$$

Due to the asymmetry of the admittance matrix, the presentation of a phase-shifting transformer is more convenient in matrix form:

$$\begin{bmatrix} \underline{I}_S \\ \underline{I}_R \end{bmatrix} = \frac{1}{jx} \begin{bmatrix} 1 & -\frac{1}{e^{j\phi}} \\ \frac{1}{e^{-j\phi}} & -1 \end{bmatrix} \begin{bmatrix} \underline{V}_S \\ \underline{V}_R \end{bmatrix} \quad (2.11)$$

2.1.3 Generation and Load Modeling

Power generation and loads are modeled by power injections at the system buses. Active power generation is normally specified for generator buses, together with the voltage magnitude that must be maintained. Loads are normally specified by their active and reactive requirements, assuming that they will stay constant for steady-state operation.

2.2 Analytical Formulation of the Load-Flow Problem

The application of the described linear mathematical models for transmission lines and transformers will generally represent a power system as an linear electrical network. Usually, a nodal or a loop analysis would be considered for solving such a network. However, even though a power system seems to be modeled as a linear network, the load-flow problem is not a linear one, due to the nonlinearity introduced by the generation and load modeling. Typically, there are two main causes of these nonlinearities. First, the power demands are given as complex powers, and not as impedances and injecting currents. Thus, constant active and reactive power models introduce a quadratic relationship between powers and voltages or currents. For a bus i having only a connected load, the corresponding fixed power demand is given as

$$\underline{S}_i = P_{d_i} + j Q_{d_i} = \underline{V}_i \underline{I}_i^* = \text{const} \quad (2.12)$$

where P_i and Q_i are the real and reactive power demands respectively, $\underline{V}_i$ is a positive sequence bus voltage and $\underline{I}_i$ is the net current entering bus i . Similarly, the second reason for the nonlinearity is that the generators are not modeled as voltage sources. They operate as power sources, with regulated voltage levels and fixed real power injection. Therefore, the load-flow equations for the steady-state operation of the system (as derived from the Kirchhoff's laws), are nonlinear algebraic equations, and iterative numerical methods are required to solve them.

Usually, the nodal analysis approach is preferred to establish a mathematical description of the system behavior. In the general case of a n -bus system, the power $\underline{S}_i$ injected into bus i (Figure 2.5) is defined by:

$$\underline{S}_i = \underline{S}_{g_i} - \underline{S}_{d_i} = P_{g_i} - P_{d_i} + j (Q_{g_i} - Q_{d_i}) \quad (2.13)$$

where the subscripts g and d denote generation and demand, respectively.

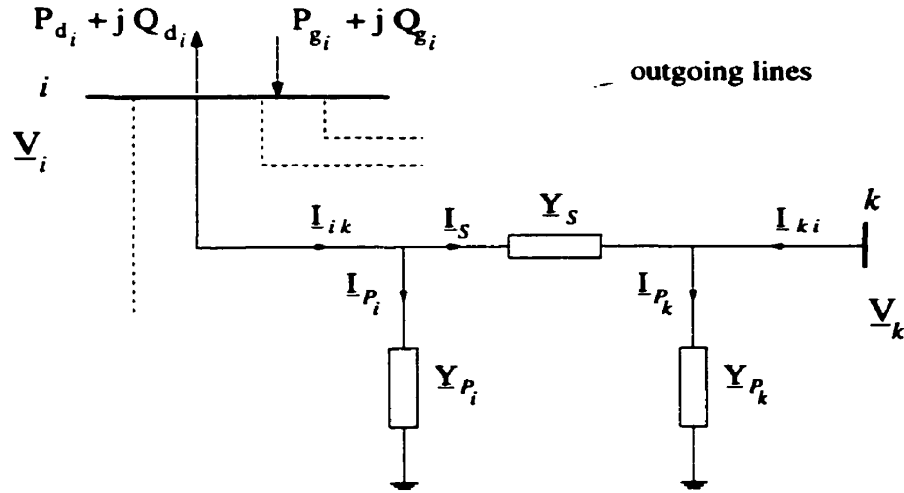


Figure 2.5: Interconnections between bus i and other surrounding buses.

The lines which interconnect bus i with other neighboring buses are, as previously adopted, represented by equivalent π -circuits. Therefore, for a current balance at bus i

$$\begin{aligned}\underline{I}_i = \frac{\underline{S}_i^*}{\underline{V}_i} &= \underline{V}_i \sum_{\substack{k=1 \\ k \neq i}}^n \underline{Y}_{pi} + \sum_{\substack{k=1 \\ k \neq i}}^n \underline{Y}_{sik} (\underline{V}_i - \underline{V}_k) \\ &= \underline{V}_i \sum_{\substack{k=1 \\ k \neq i}}^n (\underline{Y}_{pi} + \underline{Y}_{sik}) + \sum_{\substack{k=1 \\ k \neq i}}^n (-\underline{Y}_{sik}) \underline{V}_k \quad \text{for } i = 1 \dots n \quad (2.14)\end{aligned}$$

Or, in a simpler form

$$\underline{I}_i = \frac{\underline{S}_i^*}{\underline{V}_i} = \underline{y}_{i1} \underline{V}_1 + \underline{y}_{i2} \underline{V}_2 + \dots + \underline{y}_{ii} \underline{V}_i + \dots + \underline{y}_{in} \underline{V}_n \quad \text{for } i=1 \dots n \quad (2.15)$$

where

$$\underline{y}_{ii} = \sum_{\substack{k=1 \\ k \neq i}}^n (\underline{Y}_{pi} + \underline{Y}_{sik}) \quad (2.16)$$

$$\underline{y}_{ik} = \underline{y}_{ki} = -\underline{Y}_{sik} \quad (2.17)$$

Introducing *bus current* and *bus voltage* n -dimensional vectors for a given n -bus system

$$\underline{I}_{BUS} = \begin{bmatrix} \underline{I}_1 \\ \vdots \\ \underline{I}_n \end{bmatrix} \quad \text{and} \quad \underline{V}_{BUS} = \begin{bmatrix} \underline{V}_1 \\ \vdots \\ \underline{V}_n \end{bmatrix} \quad (2.18)$$

as well as an $n \times n$ bus admittance matrix $\underline{Y}_{BUS}$

$$\underline{Y}_{BUS} = \begin{bmatrix} \underline{y}_{11} & \cdots & \underline{y}_{1n} \\ \vdots & \ddots & \vdots \\ \underline{y}_{n1} & \cdots & \underline{y}_{nn} \end{bmatrix} \quad (2.19)$$

allows equations (2.14) to be expressed in a matrix form suitable for all n buses:

$$\underline{\mathbf{I}}_{\text{BUS}} = \underline{\mathbf{Y}}_{\text{BUS}} \underline{\mathbf{V}}_{\text{BUS}} \quad (2.20)$$

Bus admittance matrix $\underline{\mathbf{Y}}_{\text{BUS}}$ models the passive portion of the n -bus network, and its elements are defined by (2.16) and (2.17). Also, the $\underline{\mathbf{Y}}_{\text{BUS}}$ matrix can be very sparse because the values of the matrix elements for non-existing lines are equal to zero. (Typically, $\underline{\mathbf{Y}}_{\text{BUS}}$ can be 95% sparse, or more.)

Matrix equation (2.20) is a linear, complex equation. However, as previously mentioned, power demands and generations are not modeled by current injections and impedances, but rather as constant power values. Therefore, from (2.12) and (2.20), the power injections at each bus can be expressed as:

$$\underline{S}_i = P_i + j Q_i = \underline{V}_i \underline{I}_i^* = \underline{V}_i \sum_{k=1}^n \underline{Y}_{ik}^* \underline{V}_k \quad (2.21)$$

If the complex bus voltages and bus admittance elements are given in polar form

$$\underline{V}_i = V_i \angle \delta_i = V_i e^{j\delta_i} \quad (2.22)$$

$$\underline{Y}_{ik} = Y_{ik} \angle \psi_{ik} = Y_{ik} e^{j\psi_{ik}} \quad (2.23)$$

where V_i and Y_{ik} are the magnitudes, and δ_i and ψ_{ik} are the phase angles of $\underline{V}_i$ and $\underline{Y}_{ik}$ respectively, the power injections at each bus in polar form are:

$$\underline{S}_i = \sum_{k=1}^n V_i V_k Y_{ik} e^{j(\delta_i - \delta_k - \psi_{ik})} \quad i = 1 \dots n \quad (2.24)$$

Since both (2.21) and (2.24) are complex, there are $2n$ corresponding real equations, which together express the balance of real and reactive powers at each bus:

$$P_i = \sum_{k=1}^n V_i V_k Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) \quad (2.25)$$

$$Q_i = \sum_{k=1}^n V_i V_k Y_{ik} \sin (\delta_i - \delta_k - \psi_{ik}) \quad (2.26)$$

Therefore, a solution of the load-flow problem yields four variables at each bus of the system:

- P_i - real or active power injection ($P_i = P_{g_i} - P_{d_i}$)
- Q_i - reactive power injection ($Q_i = Q_{g_i} - Q_{d_i}$)
- V_i - voltage magnitude
- δ_i - voltage phase angle

Since only two equations correspond to each bus, and there are four variables associated with it, the number of unknowns has to be reduced to match the number of equations. As a result, from the four defined variables at each bus, two of them have to be specified at the beginning, and then the load-flow can be used to solve for remaining two. From a mathematical point of view, any of these four variables can be specified. However, in a real physical system, some of the variables can be controlled, while others are beyond regulation (depending on the devices that are connected to the affected buses). Normally, it would be desirable to specify values for controllable variables, and to solve for those that are not. According to the controllability of the variables, and thus their specified values, there are essentially three different types of buses:

- **PQ or load bus** - the total injected power $\underline{S}_i = P_i + jQ_i$ is specified. In a physical system, such buses have no generation, so P_{g_i} and Q_{g_i} are set to zero, and the load demands P_{d_i} and Q_{d_i} are given.¹
- **PV or voltage-controlled bus** - the voltage magnitude is maintained constant at a specified value by reactive power injection. An active power P_{g_i} and a

¹Also, if the generation limits of a PV bus are reached, it becomes set as a PQ bus, with $P_{d_{new}} = P_d - P_{g_{max}}$ and $Q_{d_{new}} = Q_d - Q_{g_{max}}$. Then, the two remaining unknown variables V_i and δ_i need to be determined.

voltage magnitude V_i are specified. In a system, a *PV* bus corresponds either to the generator bus with a scheduled generation P_{g_i} , at which the voltage magnitude V_i is maintained fixed by the generator's voltage regulation, or to a bus without a generator (P_{g_i} is set to zero) but with the capability to supply reactive power and thus control and maintain the voltage at a specified level.

- **swing or slack bus** - a concept introduced to balance power generation with power demands and losses. Namely, the losses that occur in transmission lines depend on the amount of current flowing through them: $P_{loss} = \sum R I^2$. Since these flows and corresponding losses are not known in advance, and can be determined only after the load-flow solution is calculated, the output power of one generator is left unspecified, to balance the system losses. Therefore, a slack bus is a generator bus at which the active power generation is not specified. It operates at constant voltage magnitude, and has an unlimited real capacity (in order to be able to compensate for all surplus power demands and losses). There is only one slack bus in the system.

Besides these bus types, the voltage phase angle is specified arbitrarily at one bus in the system (usually set to zero). This bus is defined as a *reference* bus and it is introduced to reduce the number of system unknowns since the injected powers in (2.24), or (2.25) and (2.26), depend on the phase angle differences ($\delta_i - \delta_k$) and not on the phase angles δ_i and δ_k themselves. Often the slack and reference buses are assigned at the same bus, therefore the voltage magnitude V_i and phase angle δ_i are specified, while active and reactive power generations are unknown.

With the formulation of suitable mathematical models for the system elements, and the load-flow equations for the interconnected system, together with specification of the appropriate variables at certain buses (according to bus type), the power flow problem is now defined. Numerical iterative methods are normally used to solve the resulting system of nonlinear algebraic equations to determine the unknown variables

at each bus. During the computational procedure, a mismatch between the calculated and specified values is determined:

$$\begin{aligned}\Delta P_i &= P_{i_{spec}} - P_{i_{calc}} = (P_{gi} - P_{di}) - P_{i_{calc}} \\ \Delta Q_i &= Q_{i_{spec}} - Q_{i_{calc}} = (Q_{gi} - Q_{di}) - Q_{i_{calc}}\end{aligned}\tag{2.27}$$

For the solution to a load-flow, these power mismatches would, ideally, be equal to zero. A current-mismatch expression could also be used, but the most common convergence criteria used in practice is [19]:

$$\begin{aligned}\Delta P_i &\leq c_p && \text{for all PQ and PV buses} \\ \Delta Q_i &\leq c_q && \text{for all PV buses}\end{aligned}$$

where the tolerances c_p and c_q are typically about 0.01 p.u., or less than 10% of the smallest load. The iteration procedure is successfully terminated when the power mismatches for all buses are below the required limits.

Given the values for all four variables (P, Q, V and δ) at each bus, the actual power flows in all the transmission lines may be computed. From Figure 2.6, the line current $\underline{I}_{ik}$ flowing through line $i \rightarrow k$ (measured at bus i) is equal to :

$$\underline{I}_{ik} = \underline{I}_s + \underline{I}_p = (\underline{V}_i - \underline{V}_k) \underline{Y}_{sik} + \underline{V}_i \underline{Y}_{pi}\tag{2.28}$$

while the power flows along the line ik are:

$$\begin{aligned}\underline{S}_{ik} = P_{ik} + j Q_{ik} &= \underline{V}_i \underline{I}_{ik}^* = \underline{V}_i (\underline{V}_i^* - \underline{V}_k^*) \underline{Y}_{sik}^* + \underline{V}_i \underline{V}_i^* \underline{Y}_{pi}^* \\ \underline{S}_{ki} = P_{ki} + j Q_{ki} &= \underline{V}_k \underline{I}_{ki}^* = \underline{V}_k (\underline{V}_k^* - \underline{V}_i^*) \underline{Y}_{sik}^* + \underline{V}_k \underline{V}_k^* \underline{Y}_{pk}^*\end{aligned}\tag{2.29}$$

Therefore, the solution of the load-flow equations determines the remaining unknown variables associated with each bus, and equations (2.29) give the actual power flow in each transmission line for the power system network.

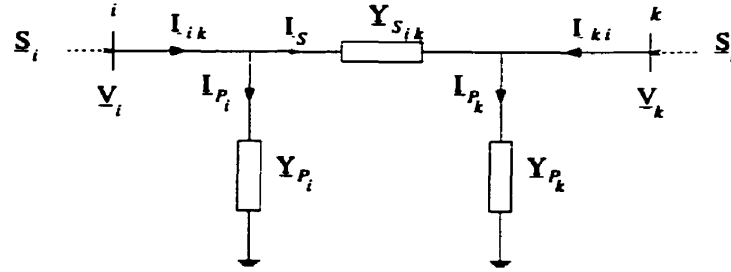


Figure 2.6: Power flows along lines

2.3 Load-Flow Calculation Methods

In the previous section, the first part of load-flow analysis, which consists of modeling the power system network and formulating the mathematical equations to represent the power flow problem, as well as specifying the known values for the control variables at each bus, was described.

The second part of the analysis is concerned with determining a suitable algorithm to solve the given system of nonlinear algebraic equations, subject to specified power and/or voltage constraints at the network buses. Generally, there are a number of different methods that have been proposed and used for power flow analysis, some of which have become more popular and widespread, and some that remain only of academic interest. Depending on the type of analysis for which the load-flow solution is used (power system planning, operational planning, or operation/control studies), different types of solutions (like accurate or approximate, off-line or on-line, unadjusted or adjusted, and single case or multiple case) and different properties of the load-flow solution method (such as high speed of computation, low computer storage space, reliability of the solution for ill-conditioned systems, versatility and simplicity) are required [19].

Y-method

One of the first digital solution methods was the Y-matrix iterative method, based on solving of the linear equation $\mathbf{I} = \mathbf{YV}$ for the bus voltages. This approach has a low storage requirement (which was important at the time of its development), but tends to converge very slowly and sometimes not at all. In order to overcome these convergence problems, certain acceleration techniques were introduced, but the total computational effort for large systems remained extensive.

Gauss-Seidel is one of the most popular methods based on Y-matrix iterative approach [19]. It is well-established method, but with the performance usually inferior to the Newton-Raphson (described later). It is often applied in commercial load flow programs in situations when other methods are unsuccessful.

Z-method

The Z-matrix method was developed with intentions to overcome the Y-matrix convergence problem. It is based on solving the set of linear equations $\mathbf{I} = \mathbf{YV}$ directly for $\mathbf{V}$, by introducing the matrix $\mathbf{Z}$ such that:

$$\mathbf{V} = \mathbf{Y}^{-1} \mathbf{I} = \mathbf{ZI}. \quad (2.30)$$

This method converges more reliably than the Y-matrix approach. However, the $\mathbf{Z}$ matrix is full, not sparse, so storage space and computation time can be quite demanding for large systems.

Newton-Raphson Method

The Newton-Raphson algorithm is a third approach to the solution of the load-flow problem (developed about at the same time as the Y-matrix method). Its convergence is very strong, but its computing time is greater than the Y-matrix and

Z-matrix methods. However, exploiting the sparsity of the Jacobian matrix and the development of the ordered triangular factorization [23] improved the performance of the Newton-Raphson method, establishing this approach as one of today's most widespread and often adopted methods in industry.

The Newton-Raphson method is an iterative numerical method which can be used to solve one algebraic nonlinear equation or a set of n simultaneous equations with n unknown variables. As an iterative numerical method it is usually applied in situations when a solution can not be derived analytically. It is one of the best general methods for solving the equation $f(x) = 0$ or a set of equations $\mathbf{f}(\mathbf{x}) = 0$ [24]. The basic idea of this iterative method is to expand a function $\mathbf{f}(\mathbf{x}) = 0$ into a Taylor's series about the point of the estimated solution $\mathbf{x}_0$, which differs from the exact solution $\mathbf{x}$ by $\Delta \mathbf{x} = \mathbf{x} - \mathbf{x}_0$. Neglecting the higher order terms of an expansion:

$$\mathbf{f}(\mathbf{x}_0 + \Delta \mathbf{x}) = \mathbf{f}(\mathbf{x}_0) + \Delta \mathbf{x} \mathbf{f}'(\mathbf{x}_0) = 0 \quad (2.31)$$

or

$$\mathbf{f}(\mathbf{x}_0) = -\mathbf{J} \Delta \mathbf{x} \quad (2.32)$$

where $\mathbf{J}$ is a Jacobian matrix with elements defined by $J_{ik} = \frac{\partial f_i}{\partial x_k}$. Therefore, by equation (2.32) a nonlinear problem may be approximated by a linear matrix equation, which can be solved for $\Delta \mathbf{x}$, to yield a new solution:

$$\begin{aligned} \mathbf{x}^{k+1} &= \mathbf{x}^k + \Delta \mathbf{x} \\ \mathbf{x}^{k+1} &= \mathbf{x}^k - [\mathbf{J}(\mathbf{x}^k)]^{-1} \mathbf{f}(\mathbf{x}^k). \end{aligned}$$

Here, $\mathbf{x}^{k+1}$ and $\mathbf{x}^k$ are the values of $\mathbf{x}$ in the k -th and $(k+1)$ -th iteration steps, respectively.

In terms of load-flow analysis, the matrix equation $\mathbf{f}(\mathbf{x}) = 0$ corresponds to the set of $2n$ equations for the real and reactive power injections (2.25) and (2.26), and the variables $\mathbf{x}$ are the voltage magnitudes and voltage phase angles:

$$\mathbf{x} = \begin{bmatrix} \delta \\ \mathbf{V} \end{bmatrix} \quad \mathbf{f}(\mathbf{x}) = \begin{bmatrix} \mathbf{P} - \mathbf{P}(\delta, \mathbf{V}) \\ \mathbf{Q} - \mathbf{Q}(\delta, \mathbf{V}) \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} \quad (2.33)$$

Here, $\mathbf{P}$ and $\mathbf{Q}$ are vectors of specified power values, and $\mathbf{P}(\delta, \mathbf{V})$ and $\mathbf{Q}(\delta, \mathbf{V})$ correspond to values calculated from (2.25) and (2.26) at each iteration; $\Delta \mathbf{P}$ and $\Delta \mathbf{Q}$ are the calculated power mismatches.

The load-flow problem equation (2.32) may now be expressed as:

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \frac{\partial \mathbf{P}}{\partial \delta} & \frac{\partial \mathbf{P}}{\partial \mathbf{V}} \\ \frac{\partial \mathbf{Q}}{\partial \delta} & \frac{\partial \mathbf{Q}}{\partial \mathbf{V}} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \mathbf{V} \end{bmatrix} \quad (2.34)$$

and the new values of the voltage phase angles and voltage magnitudes at iteration step $(k + 1)$ are equal to:

$$\begin{bmatrix} \delta^{k+1} \\ \mathbf{V}^{k+1} \end{bmatrix} = \begin{bmatrix} \delta^k \\ \mathbf{V}^k \end{bmatrix} + \left[\begin{bmatrix} \frac{\partial \mathbf{P}}{\partial \delta} & \frac{\partial \mathbf{P}}{\partial \mathbf{V}} \\ \frac{\partial \mathbf{Q}}{\partial \delta} & \frac{\partial \mathbf{Q}}{\partial \mathbf{V}} \end{bmatrix}_{\delta^k, \mathbf{V}^k} \right]^{-1} \begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix}. \quad (2.35)$$

The derivatives in each sub-matrix of the Jacobian matrix $\mathbf{J}$, according to equations (2.25) and (2.26), are of the form:

$$\frac{\partial P_i}{\partial \delta_i} = - \sum_{\substack{k=1 \\ k \neq i}}^n V_i V_k Y_{ik} \sin (\delta_i - \delta_k - \psi_{ik}) \quad (2.36)$$

$$\frac{\partial P_i}{\partial \delta_k} = V_i V_k Y_{ik} \sin (\delta_i - \delta_k - \psi_{ik}) \quad (2.37)$$

$$\frac{\partial P_i}{\partial V_i} = \sum_{\substack{k=1 \\ k \neq i}}^n V_k Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) + 2 V_i Y_{ii} \cos \psi_{ii} \quad (2.38)$$

$$\frac{\partial P_i}{\partial V_k} = V_i Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) \quad (2.39)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq i}}^n V_i V_k Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) \quad (2.40)$$

$$\frac{\partial Q_i}{\partial \delta_k} = -V_i V_k Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) \quad (2.41)$$

$$\frac{\partial Q_i}{\partial V_i} = \sum_{\substack{k=1 \\ k \neq i}}^n V_k Y_{ik} \sin (\delta_i - \delta_k - \psi_{ik}) - 2V_i Y_{ii} \sin \psi_{ii} \quad (2.42)$$

$$\frac{\partial Q_i}{\partial V_k} = V_i Y_{ik} \cos (\delta_i - \delta_k - \psi_{ik}) . \quad (2.43)$$

Therefore, at each iterative step, the new values for the voltage magnitudes and voltage phase angles are calculated based on the solution from the previous step, as well as the coefficients of Jacobian matrix for that particular step and the values of the power mismatches from the previous iteration. The power mismatches are calculated for the new values $\mathbf{V}^{k+1}$ and $\boldsymbol{\delta}^{k+1}$. The iterative process terminates when the values of the mismatches $\Delta \mathbf{P}$ and $\Delta \mathbf{Q}$ are less than the specified tolerances.

The number of required equations depends on the number and types of buses. For each PQ bus, where both V_i and δ_i are unknown, two equations are required. At each PV bus, only δ_i is unknown, so only one equation is needed. For the slack bus both V_i and δ_i are given, and no equation is required.

A major problem of the Newton-Raphson method is the necessity to evaluate and invert a Jacobian matrix that can be very large. Moreover, the elements of this matrix are not constant, but change with each iteration, so the inversion of $\mathbf{J}$ has to be done at each iterative step. On the other hand, for load-flow calculations, the Jacobian matrix is very sparse (as sparse as the $\mathbf{Y}_{BUS}$ matrix). This feature was the main motivating point behind major improvements that were introduced to make the computational time and storage requirements of this otherwise very robust, reliable and fast (in convergence²) Newton-Raphson method, competitive with other

²An extensive investigation of the convergence of the Newton-Raphson method was done by Stagg and El-Abiad [25], resulting in the conclusion that the number of iterations is quite independent of

algorithms.

Sparsity programming exploits the fact that a majority of the Jacobian matrix elements are equal to zero. (The sparsity of the Jacobian matrix can be as high as 95% or greater.) As a result, only those elements that are not equal to zero need to be stored together with their positions in the matrix. Although it is now necessary to store three values for each non-zero element, this method of compact storage usually reduces the required memory by a great extent for large sparse matrices.

Moreover, the sparsity of the Jacobian matrix can be used for improving the speed of solving for its inverse. Namely, for Gaussian elimination, if the matrix rows are reordered in such a way that as many as possible of the nonzero elements are located to the right of the main diagonal, then the number of steps needed to transform this ordered matrix into upper-triangular form is reduced. Thus the computational time required to solve the resulting linear system is far less than in the case of the non-reordered Jacobian matrix.

The Newton-Raphson method is based on calculations of the complete Jacobian matrix at each iterative step, therefore it is the *AC full (Newton-Raphson) load-flow*. This method yields accurate results, but its performance can be too slow and costly. In cases when less accurate solutions are good enough, some simplifications in the calculation procedure can be introduced, leading to the *Decoupled load-flow*, *Fast decoupled load-flow*. Finally, the fastest but least accurate *DC load-flow* method simplifies the power flow equations themselves, through their linearization.

Decoupled Load-Flow

Decoupling techniques are based on the fact that in practical power systems there is a strong dependence between active power flows and voltage phase angles, and also between reactive power flows and voltage magnitudes. Further, the coupling

the size of the power system network under study.

between these two components ($P - \delta$ and $Q - V$) is relatively weak and the corresponding elements in the Jacobian matrix are relatively small. Consequently, the corresponding sub-matrices of the Jacobian matrix can be neglected:

$$\frac{\partial \mathbf{P}}{\partial \mathbf{V}} \approx 0$$

$$\frac{\partial \mathbf{Q}}{\partial \delta} \approx 0,$$

thereby yielding two smaller matrix equations [26]

$$\frac{\partial \mathbf{P}}{\partial \delta} \Delta \delta = \Delta \mathbf{P} \quad (2.44)$$

$$\frac{\partial \mathbf{Q}}{\partial \mathbf{V}} \Delta \mathbf{V} = \Delta \mathbf{Q}. \quad (2.45)$$

Fast Decoupled Load-Flow

This method is derived from the decoupled load-flow, by keeping the decoupled Jacobian matrix constant for all iterations. This simplification is based on certain approximations that can be introduced. Namely, the voltage magnitudes in the calculation of the are all set to $\mathbf{B}'$ and $\mathbf{B}''$ matrices $V_i = 1.00 \text{ p.u.}$, and the differences between voltage phase angles across transmission lines are assumed to be small, so that $\cos(\delta_i - \delta_k) \approx 1$ and $\sin(\delta_i - \delta_k) \approx 0$. Also, the resistances r_{ik} are assumed to be much smaller than the line reactance x_{ik} , so that the conductances g_{ik} can be neglected. The resulting fast decoupled load-flow equations are [27]:

$$\mathbf{B}' \Delta \delta = \frac{\Delta \mathbf{P}}{\mathbf{V}} \quad (2.46)$$

$$\mathbf{B}'' \Delta \mathbf{V} = \frac{\Delta \mathbf{Q}}{\mathbf{V}}. \quad (2.47)$$

The elements of the $\mathbf{B}'$ and $\mathbf{B}''$ matrices are the imaginary parts of admittance matrix. Moreover, the shunt reactances and off-nominal in-phase taps are omitted from matrix $\mathbf{B}'$, and the influence of phase-shifting transformers is neglected in matrix $\mathbf{B}''$. Since both $\mathbf{B}'$ and $\mathbf{B}''$ are constant, their elements need to be evaluated only once during the complete iterative solution procedure.

DC Load-Flow

Linearized or “*DC*” load-flow is an even further simplification of the power flow equations, which effectively reduces the system to a linear circuit analysis problem. Assuming that all angular differences are less than 30° (so that $\cos(\delta_i - \delta_k) \approx 1$ and $\sin(\delta_i - \delta_k) \approx (\delta_i - \delta_k)$), and also assuming that for all lines $x_{ij} \gg r_{ij}$ (so that $g_{ij} \approx 0$), together with neglecting the shunt admittance and setting $V_i = 1.00 \text{ p.u.}$, the matrix equation reduces to [28]:

$$\mathbf{P} = \mathbf{B} \boldsymbol{\delta} \quad (2.48)$$

where

$$\begin{aligned} B_{ik} &= -\frac{1}{x_{ik}} & i, k \neq ref \\ B_{ii} &= \sum_k \frac{1}{x_{ik}} & i \neq ref \\ B_{ik} &= 0 & i, k = ref. \end{aligned} \quad (2.49)$$

This is a very simple, but fast approach that does not take into consideration reactive power flows and, as mentioned earlier, neglects a number of other properties of the power system network. However, this approach can be used for rough power system calculations.

Chapter 3

Development of Artificial Power System Networks and Some Possible Approaches

The necessity of generally accessible power system networks suitable for the testing of algorithms applied in power system analysis, and the lack of such networks, may be overcome by developing suitable artificial networks and corresponding data sets. Consequently, exploring the possibilities of generating such artificial systems and data for the purpose of full load-flow studies is indicated as an interesting and important research area. In addition to this primary purpose, for load-flow studies, application of the developed power systems for other power system analysis problems may also be considered, because a reasonable network for any other study (e.g. contingency analysis, reliability, stability, etc.) would be expected to have a stable and realistic power flow solution. Given a reasonable artificial load-flow test network, further upgrades can be made by introducing the additional data necessary for other types of analysis.

The objective of this thesis is to investigate the possibility of developing an algorithm suitable for the generation of load-flow test networks. Therefore, all the evaluated methods are primarily regarded from this perspective.

3.1 General Considerations in the Development of Power System Networks

3.1.1 Required Load-Flow Test Network Data

In the previous chapter, the load-flow problem and its corresponding network representations were presented. An adequate set of data for a full power flow analysis should incorporate the following three subsets:

1. **topology data** which describe the size of the system (the number of buses and the number of lines) and the interconnections between the buses.
2. **network parameters** that define the relevant physical properties of the network elements according to the adopted equivalent models. Typically, these include line lengths, line impedances and admittance per unit length, and the maximum ampacity of the lines. Also, transformer impedances and tap settings are given. These network parameters, together with the topology data, define the elements of the bus admittance matrix $\mathbf{Y}_{BUS}$ ((2.16), (2.17) and (2.19)).
3. **bus parameters** give the active and reactive power demands at each bus, the type of bus, and the specific data necessary for certain bus types, such as, scheduled power generation and voltage magnitude for PV buses (along with the minimal and maximal values of active and reactive generation $P_{g_{max}}$, $P_{g_{min}}$, $Q_{g_{max}}$ and $Q_{g_{min}}$). These data also include the specifications of the reference and slack bus(es).

The solutions to artificial power system networks should respect the same voltage tolerances, as well as the stability and thermal limits, that constrain practical power grids. Moreover, it is essential to assign the network parameters in such a way to ensure the convergence of the load-flow solution. Otherwise, the network will be of little practical use.

3.1.2 Network Development

The generation of a synthetic power network can be regarded, in a way, as a process of expanding an existing system by adding new load or generation points, or interconnecting existing buses. This technique can be approached in different ways. One possibility is to regard the process of network development as an iterative procedure such that the addition of each new node or line can be accomplished in the same, or a similar manner. The “starting point” is a given, known, network. For the moment, it is of no importance how this “starting” network is obtained, since only potential approaches to the iterative process of adding new elements are currently of interest. Therefore, starting with a given network, at each iterative step the size of the network will increase by adding new nodes and lines to the existing system. After determining a new bus to be added, together with its power demands and/or generation, the way it will be appended to the existing system and the necessary adjustments needed to accommodate this new connection have to be determined. The new extended system has to operate respecting the original required constraints, and will become the starting point for the next iterative growth.

The addition of a new bus can effect a change in the state variables, as well as in the power-flows along the lines. These changes, however, will not only depend on the parameters of the new point, such as the generated and/or demanded power (P_g, Q_g, P_d and Q_d), but also on the parameters of the connecting line(s). In addition, connections at different buses of the system can produce different effects on the existing network.

Typically, planning studies involve the problem of expanding a given power system. In the process of expanding an existing network, different aspects of the proposed solution have to be evaluated. Usually, only a small subset of all possible extensions are considered. They can be chosen with respect to geographical location, transmission line costs, and the state of the existing network. For example, in reality,

it is very unlikely that a new load point will be connected to some remote existing nodes (e.g. at the other side of the network), when nearby nodes are available. This constraint allows for a narrowing, especially within large networks, of the subset of connecting points that may be of interest.

Even though the same, or a similar, amount of change of load at each of the given buses is examined, it will not be “felt” in the existing system in the same way. The extension of the network at one point may produce overflows or voltage disturbances, while the same change at another point may only increase the values of some variables, without approaching the transmission loadability limits. Of course, it would be beneficial to find a solution which will use the given network in the most efficient way and, if possible, leave some room for further changes or expansions. However, if a given system is already near its limits, it might not be possible to satisfy the expansion problem within the confines of the existing network, but only through some changes such as raising power-flow limits by adding new circuits in parallel with existing ones, or by improving reactive power flows through installing new equipment such as transformers and/or compensators. The improved network will have more flexibility to accommodate additional loads and further extensions, but will also add some expenses that have to be taken into consideration when making a final decision on how the existing network will be expanded. Also, it is not always suitable or necessary to add a new bus using only one line, by attaching it to only one point of the given system. Depending on the power demand and generation, it might be possible that connections to two, or even three locations are more appropriate.

The third aspect from which potential network expansions can be regarded is the cost of the proposed new line. The shortest distance between two points does not necessarily mean that the transmission line along that corridor will be of the least cost. Actually, it might happen that that solution will not be even feasible (due to some obstacles) or that it might be excessively expensive and thus not even worth considering. Different factors can affect the cost, and then, the location of

the new corridor. Some of them might be of geographical nature, while others might be the high cost of the land, high environmental impact, or a long-term decision to follow some pre-existing paths (e.g. around the big cities). Also, each network (or subnetwork) may have a specific “shape”, and it may be desired to have the new transmission lines respect and preserve the given configuration. Finally, as previously mentioned, expenses associated with upgrading the existing system in order to maintain any required voltage and power limits, should be considered.

Therefore, examining the process of selecting a planned extension to the system can give insight into the problems associated with an iterative growth of a given system, and potential methods for resolving them.

Influence of a New Bus on an Existing Network

Suppose one is given an existing network, which is described by its parameters, together with the known set of state variables: active and reactive power generation P_g and Q_g , active and reactive power demand P_d and Q_d (or power injections $P = P_g - P_d$ and $Q = Q_g - Q_d$), as well as voltage magnitude V and voltage phase angle δ . The addition of a new bus, and/or a new transmission line can affect the existing system in several ways:

- The $\underline{Y}_{BUS}$ matrix will be expanded by adding one row and one column. If the connection is done at node k the new corresponding elements will be:

$$Y_{(n+1)(n+1)} = y_{l_{new\ line}} + j \frac{b_{sh_{new\ line}}}{2} \quad (3.1)$$

$$Y_{(n+1)k} = Y_{k(n+1)} = -y_{l_{new\ line}} \quad (3.2)$$

$$Y_{kk}^{new} = Y_{kk}^{old} + y_{l_{new\ line}} + j \frac{b_{sh_{new\ line}}}{2} \quad (3.3)$$

$$Y_{(n+1)j} = 0 \quad j \neq k$$

$$Y_{j(n+1)} = 0 \quad j \neq k$$

- The total power demand and generation will change in order to accommodate the modifications in network topology, the new load and generation, losses and reserve (if changed).
- Since the total power demand of the system has been altered, a new economic dispatching among the generating units should be determined.
- Due to modifications in generation, load, and system configuration, the power-flow along the transmission lines will also change. The power-flow solution for the new network will yield new values for the state variables P , Q , V and δ .

Starting from a feasible operating point for the given system, the intention is to determine how the change in configuration, power demands and generation at different locations in the system will influence the existing network.

Two apparent problems can be considered at this stage. The first is associated with the distribution of the new load demands among the available generating units. The second problem is to examine how the state variables and power flows will change with the addition of a new bus and the associated new power demand.

The first problem of the new scheduled generation can be addressed by solving the economic dispatching problem for the updated values of the power demands. Another, simplified, approach would be to distribute the new load among the generating units in proportion with their maximum power ratings, with proportionality factor:

$$\gamma_i = \frac{P_{i_{max}}}{\sum_{i=1}^n P_{k_{max}}}. \quad (3.4)$$

Then, the new values of the power outputs would be:

$$P_{i_{new}} = P_{i_{old}} + \gamma_i P_{new \text{ load demand}}. \quad (3.5)$$

Solving for economic dispatching is usually the accepted method. The proportionality factors give suboptimal solution, and are often used for quick adjustments between dispatches.

The solution to the second problem of modified power flows can be regarded from different points of view, considering different methods. If highly accurate results are not needed, losses along the lines can be neglected. Then, the system will be linearized and, therefore, easier to solve. In this case, the investigation is based on a *DC* load-flow solution, and will only yield a rough picture of the system. For more accurate results, the losses and other parameters should be taken into consideration, and a full load-flow calculation should be used. Also, methods based on *sensitivity analysis* which investigate how the state variables change with respect to perturbations in some parameters of the system, could be considered. Finally, an *optimal power flow* approach might yield a method that simultaneously addresses both the problem of new generation and new power-flows along the lines.

The all three above-mentioned methods are presented next, reflecting their applicability to the problem of network expansion. Although these methods are often useful in practical power systems planning studies, they are not selected for the suggested algorithm of iterative generation of synthetic power systems. Instead, a new approach that treats network expansion in rather a different manner is proposed. It is based on the idea to maintain parameters and power flows of the existing power system intact, while introducing a new element to expand a given network. Also, a comparison between “planning” methods and a new “backwards” method is discussed.

3.2 DC Load-Flow Approach

The linearized or *DC* load-flow equation is defined in (2.48) as:

$$\mathbf{P} = \mathbf{B} \boldsymbol{\delta}. \quad (3.6)$$

The net power injections $\mathbf{P}$ are defined for all buses except the reference bus, and the elements of the $\mathbf{B}$ matrix are as defined in the (2.49). Therefore, solving (3.6) for voltage angles $\boldsymbol{\delta}$, for the given active power injections $\mathbf{P}$ and the $\mathbf{B}$ matrix, gives:

$$\boldsymbol{\delta} = \mathbf{B}^{-1} \mathbf{P} \quad (3.7)$$

$$\boldsymbol{\delta} = \mathbf{X} \mathbf{P}^1. \quad (3.8)$$

The power flows along the lines depend on both the voltage angle differences between the buses and the line admittance:

$$P_{ik} = -B_{ik} \delta_{ik} = \frac{\delta_i - \delta_k}{x_{ik}} \quad (3.9)$$

or, in matrix form

$$\mathbf{P}_\ell = \text{diag } \mathbf{x}_\ell \mathbf{A} \cdot \boldsymbol{\delta} \quad (3.10)$$

where

$\mathbf{A}$ is the incidence matrix; and

$\text{diag } \mathbf{x}_\ell$ is a diagonal matrix of the line reactances x_{ik} :

$$\begin{bmatrix} x_{l1} & 0 & \cdots & 0 \\ 0 & x_{l2} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & \cdots & x_{l_{n_l}} \end{bmatrix}$$

¹Since $\mathbf{B}$ is singular, $\mathbf{X}$ is not exactly its inverse, but the modification obtained by inverting a sub-matrix $\mathbf{B}_*$ (submatrix of $\mathbf{B}$ when the rows and columns for the reference bus are removed), and then adding a row and a column of zeros at the index of the reference bus.

When examining the influence of the addition of a new node to the existing network, it is of interest to investigate how the variations in power injections and the new transmission lines will influence the overall behavior of the system. In the DC load-flow method the lines are considered lossless, so they do not contribute to the power system demands. It is only the increase in power demand at the point of connection that is “felt” in the system. As a result, it is possible to investigate the behavior of the existing system without really modeling the complete addition of a new line. The simulation of this new connection can be done by only changing the injected power at the buses at which these connections are considered. Therefore, the **B** matrix may remain the same throughout the examination procedure, and is only changed when it is finally determined where the new bus will be connected.

This linearized approach can yield fast insight into the effects an additional power demand would have on the existing network. However, the intention is to develop artificial power system networks suitable for full load-flow investigations. Therefore, an approach based only on the DC load-flow method may not yield a complete solution to the problem of iteratively assembling a power system network, and the corresponding data sufficient for testing a full load-flow, because certain network parameters, together with the influence of the reactive power flows and losses significant for an accurate representation, are neglected.

3.3 Network Sensitivity Analysis

The main idea behind the network sensitivity methods is to analyze how the perturbations of some operating parameters will affect the behavior of the examined system. Like in other methods applied in power system analysis, there are basically two approaches: one is based on a nonlinear model, and the other is based on a linearized approximation.

non-linear model This technique is based on the non-linear relations between state variables and control variables or parameters. It is of interest to investigate how a modification in control variables or parameters can influence a change in the values of the state variables. The non-linear network sensitivity method is often used in the voltage stability problem ([29], [30]), because it can reveal the perturbations to which the power system is the most sensitive, and which disturbances may lead to the violation of voltage limits, or even voltage collapse. The load-flow equations can be written in the form :

$$\mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{p}) = \mathbf{0} \quad (3.11)$$

where $\mathbf{x}$ is a vector of state variables ($\mathbf{V}$ and δ at PQ buses), $\mathbf{u}$ is a vector of control variables ($\mathbf{P}_g$ and $\mathbf{V}$ at PV buses), and $\mathbf{p}$ is a vector of parameters ($\mathbf{P}_d$ and $\mathbf{Q}_d$). A Taylor's series expansion (neglecting higher order terms) yields:

$$\Delta \mathbf{f} = \mathbf{f}_x \Delta \mathbf{x} + \mathbf{f}_u \Delta \mathbf{u} + \mathbf{f}_p \Delta \mathbf{p} = \mathbf{0}. \quad (3.12)$$

Therefore, the sensitivity in state variables $\mathbf{x}$ can be expressed as:

$$\Delta \mathbf{x} = -\mathbf{f}_x^{-1} \mathbf{f}_u \Delta \mathbf{u} - \mathbf{f}_x^{-1} \mathbf{f}_p \Delta \mathbf{p} \quad (3.13)$$

$$\Delta \mathbf{x} = \mathbf{S}_{xu} \Delta \mathbf{u} + \mathbf{S}_{xp} \Delta \mathbf{p} \quad (3.14)$$

where matrices $\mathbf{S}_{xu}$ and $\mathbf{S}_{xp}$ represent the sensitivities of state variables $\mathbf{x}$ to variations in control variables $\mathbf{u}$ and input parameters $\mathbf{p}$, respectively.

The Taylor's series expansion assumes that the function $\mathbf{f}$ has its first $(n + 1)$ derivatives (n is the number of terms in the series expansion). This condition is satisfied in the case of the power-flow equations. However, power series expansions are valid only in a limited neighborhood around the point of interest. In the case of voltage stability, this condition might be valid. But, when the point of investigation is farther away from the given operating point, it can limit the

applicability of this approach. Unfortunately, in the network expansion problem it is not always certain whether the new state would be close enough to the given operating condition. Consequently, the constraint of the “closeness” of the two operating points may often be a limiting factor for this type of analysis. Moreover, it might be hard to predict when this type of constraint would be violated.

Even though it would be useful to examine how a change in load, or the addition of new lines, would influence the state variables and the flows in a given network, it may not be always possible to determine these changes with the desired accuracy using only sensitivity analysis, because this method is valid only for small changes around the given operating point, and there is no guarantee that the introduced changes would be sufficiently small. Actually, the expected perturbations may sometimes be quite large.

linear model Sensitivity analysis based on linear models is mainly used in contingency analysis, when the objective is to investigate the behavior of the system in the case of single failure events. The outage of any component in the system - a line or a generator - will influence the operation of the system, and may cause power-flows or voltages to fall outside the required limits.

The possible overloads for a given contingency are usually evaluated through the network sensitivity factors. They show the change in line flows for modifications in generation or in network configuration. Actually, only an approximate value of a change is provided, since the factors are derived from a DC load-flow, in which voltage magnitudes are considered constant (and equal to 1.0 p.u.) and lines are considered lossless. In contingency analysis, basically two types of sensitivity factors are used [28]:

1. generation shift distribution factor
2. line outage distribution factor

The first factor takes into consideration the failure of a generator, while the second examines the outage of a line. When expanding a given network, it is of interest to see how a shift in generation affects system behavior. The process of adding a new line is not only associated with a change in the flows along the lines, but also with an expansion of the $\mathbf{Y}_{BUS}$ matrix itself. Exploiting the generation shift distribution factor for evaluating modifications in power flows and generation might seem useful. However, the scenario when the line outage distribution factor is applied, is quite the opposite of the situation when a new line is added to an existing system. Therefore, utilization of the second distribution factor will not be considered.

Generation Shift Factor

Generation shift factor $a_{\ell i}$ represents the change in load-flows along the line ℓ due to a perturbation in the generation at bus i . It is defined as:

$$a_{\ell i} = \frac{\Delta P_{flow_{\ell}}}{\Delta P_i} \quad (3.15)$$

where $\Delta P_{flow_{\ell}}$ is the variation in the active power flow on the line ℓ that occurs when the generation at bus i changes by the amount of ΔP_i .

The assumption made here is that the change in generation ΔP_i is fully compensated for at the slack bus, while all other generators remain fixed. If there is a generator outage at bus i , the change of generation at this bus is equal to its generation before the failure, i.e.

$$\Delta P_i = -P_i^o. \quad (3.16)$$

Because of the new power distribution in the network, new power flows in the

lines can also appear. The new flow on each line is given as:

$$P_{flow_\ell}^{new} = P_{flow_\ell}^o + a_{\ell i} \Delta P_i \quad (3.17)$$

where $P_{flow_\ell}^{new}$ is the new power-flow, after the change in generation at bus i , $P_{flow_\ell}^o$ is the power-flow along the line before the failure, and $a_{\ell i}$ is the generation sensitivity factor.

Another way of compensating for a generation outage at bus i is to distribute the lost generation power P_i^o among all the generators, in proportion to their maximum power outputs P_{max_k} . Then, the portion of the power ΔP_j that would be compensated by the generator at bus j is:

$$\gamma_{ji} = \frac{P_{max_j}}{\sum_{\substack{k=1 \\ k \neq i}}^j P_{max_k}}. \quad (3.18)$$

Then, by superposition, the new power-flow on line ℓ would be :

$$P_{flow_\ell}^{new} = P_{flow_\ell}^o + \sum_{\substack{j \\ j \neq i}} a_{\ell j} \gamma_{ji} \Delta P_i. \quad (3.19)$$

Recalling that the power-flow along the line ik is :

$$P_{ik} = \frac{1}{x_{ik}} (\delta_i - \delta_k) = b_{ik} (\delta_i - \delta_k), \quad (3.20)$$

the generation sensitivity factor on line ik due to a generator failure at bus m may be given by:

$$a_{\ell ik} = \frac{dP_{ik}}{dP_m} = \frac{d}{dP_m} \left(\frac{1}{x_{ik}} (\delta_i - \delta_k) \right) \quad (3.21)$$

i.e.

$$a_{\ell ik} = \frac{1}{x_{ik}} \left(\frac{d\delta_i}{dP_m} - \frac{d\delta_k}{dP_m} \right). \quad (3.22)$$

Even though the application of generation distribution factors would be a fast and easy procedure to examine changes in power flows due to modifications in generation, some problems arise. First, these factors are based on linearized DC models, so certain characteristics of the power system networks, important for more accurate results, are neglected. Second, the given factors are only useful when generation is shifted to cover for the outage of a generator, while the total generated power of the system has not been changed. In order to overcome the limitations of generation shift distribution factors, another set of *generalized distribution factors* were developed by Ng [31]. System generation is not constant for the improved parameters. Still, the change in the total system load is not attached to only one bus, but conformingly distributed among the load demands across the network.

When extending a given network, the objective is to investigate how a change in power demand at only one point, when compensated by all the available generation units, or any subset of them, would affect the flows along the lines. However, neither of the linear-model methods takes this type of change into consideration.

3.4 Optimal Power Flow Approach

The Optimal Power Flow (OPF) problem solves for the optimal steady-state operating conditions of a given power system. It was developed from the Economic Dispatching problem by incorporating the power flow equations. Generally, different constrained optimization problems may be considered in operation and planning studies of power systems, like minimizing the operating costs of generating units, optimizing the voltage profile of the system, or minimizing system losses. Fundamentally, the problem consists of minimizing a functional of variables $\mathbf{P}$, $\mathbf{Q}$, $\mathbf{V}$ and δ ,

while satisfying the load-flow equations and a set of inequality constraints which express the operating limits of the generation and transmission equipment. Therefore, a general mathematical formulation of the problem [17] is:

Minimize a scalar functional

$$F(\mathbf{P}_g, \mathbf{Q}_g, \mathbf{V}, \boldsymbol{\delta}) \quad (3.23)$$

subject to

$$P_{g_i} - P_{d_i} = f_{p_i}(\boldsymbol{\delta}, \mathbf{V}) \quad (3.24)$$

$$Q_{g_i} - Q_{d_i} = f_{q_i}(\boldsymbol{\delta}, \mathbf{V}) \quad (3.25)$$

$$r_i(P_{g_i}, Q_{g_i}, V_i) \leq 0 \quad (3.26)$$

$$h_j(\boldsymbol{\delta}, \mathbf{V}) \leq 0 \quad (3.27)$$

where

P_{d_i} and Q_{d_i} are the active and reactive power demands at bus i , respectively

$r_i(P_{g_i}, Q_{g_i}, V_i) \leq 0$ is a set of local constraints, such as voltage limits and/or generation limits

$h_j(\boldsymbol{\delta}, \mathbf{V}) \leq 0$ represents the maximum transfer limits of the transmission circuits.

The equality constraints correspond to the set of load-flow equations. The inequality constraints (3.26) are usually expressed in the form of bound limits:

$$P_{g_i}^{min} \leq P_{g_i} \leq P_{g_i}^{max} \quad (3.28)$$

$$Q_{g_i}^{min} \leq Q_{g_i} \leq Q_{g_i}^{max} \quad (3.29)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (3.30)$$

while (3.27) are of the form:

$$I_{ik} \leq I_{ik}^{max} \quad (3.31)$$

$$I_{ki} \leq I_{ki}^{max} (= I_{ik}^{max}). \quad (3.32)$$

For the problem of expanding a given network, the connection of a new power transmission line and demand bus will affect the system differently for different points of connection. Selecting a point which would introduce the least change in the network operation, or at least, lead to the smallest violations of the given constraints, would be beneficial. Therefore, the procedure of determining where the new bus should be added could consist of solving an OPF problem for a set of preselected nodes, to determine the bus which would result in the least impact. The intention is to find a distribution of the new load among the available units such that:

- operation costs are minimized
- each bus voltage is as close as possible to 1.00 p.u.
- overloading on the transmission lines is minimized.

The objective function in this problem can be cast in the form:

$$F = \sum c_i(P_{gi}) + \omega_1 \sum_{i=1}^n (V_i - 1)^2 + \omega_2 \sum_{lines} P_{flow_l}. \quad (3.33)$$

Generally, the solution to the OPF problem may tolerate violations of some constraints (“soft” constraints), while the violation of “hard” constraints would result in an infeasible solution. Typically, in the OPF problem the voltage and line flow constraints are imposed as “hard” limits. In this case, however, that may not be suitable because it is not known in advance whether a new network will maintain

all the state variables within the desired limits, or not. That is the reason why the voltage and line loading limits are introduced in an objective function through penalty terms. Thus, the algorithm would still try to find a solution which keeps the bus voltages and line power flows, as much as possible, within the specified tolerances, and the violation of the required limits would not terminate the search process. Also, the information about the constraint violation variables can give insight into which corrective methods may be used to upgrade the system so that it can accommodate the new configuration. As previously mentioned, the system's operation may be improved through the addition of new circuits connected in parallel with the existing ones, or by installing devices for reactive power flow control.

Therefore, the solution to the OPF problem would yield the values of the power injections $\mathbf{P}$ and $\mathbf{Q}$, voltage magnitudes $\mathbf{V}$, and voltage phase angles δ for which the function F reaches its extremum. If all of these values are within the required limits, then the obtained results should be compared with feasible solutions corresponding to other points of connection. If any of the variables are outside the desired limits, an upgrade of the system may have to be considered. The final decision on where to connect the new line and demand bus should be based on the extremum value of F and the smallest upgrading costs.

This approach would simultaneously yield accurate results both for the economic dispatching and load-flow problems. The optimal solution should indicate how to use and expand the network most efficiently. Also, this approach imitates the real procedure of planning studies, since it is looking for the most efficient and least costly solution.

On the other hand, the OPF problem is time consuming, especially for larger systems. In each expansion step it would need to be solved a number of times, in order to best choose the final point for the connection from the given set. Also, problems of existence and convergence of solutions for particular new network configurations

may arise. These potential disadvantages may justify an effort to search for another, faster and more “convergence controllable” approach.

3.5 New “Backwards” Approach

The previously discussed “system planning” approaches seem to follow the “natural” path of expanding a given network. Starting from a given system, they investigate the effect that the addition of a new bus would have on the existing grid, since the values of the state variables over the entire network would be affected. Generally, some of these changes could be significant, while others may not be so strong. However, certain voltage and/or power flow constraints may be violated by the considered addition, and in that case it would be necessary to introduce suitable adjustments in order to accommodate the resulting changes and keep the network within the required limits. Modifications of the network may include the addition of new lines in parallel with existing ones, or the introduction of new equipment for improving reactive power flows. In both cases, the parameters of the existing portion of the network would change, and the power flow solution for the starting network would no longer be valid. Also, it is not always certain that the solution to the newly adjusted network will even converge, and it would not necessarily be clear which of the network changes were the cause of the instability. In planning studies, this problem might not be so critical, because the process of determining the final solution involves a number of evaluation stages, and is not completely automated. Thus, infeasible solutions can be investigated and either removed or corrected by the designer.

However, in the process of generating artificial power system networks it would be desirable and more efficient to develop an algorithm with a certain degree of “autonomy”, so that decisions could be made without the necessity of direct supervision by the user. One possible approach to achieve an automated development of power

system networks would be to find a way to introduce a new bus and the corresponding network changes while retaining the load-flow solution for the given input system. If such a type of network expansion can be accomplished, an iterative approach based on this method would seem to offer a good solution to the problem of developing artificial power system networks. The intention of the proposed “backwards” method is to investigate a possible approach to the expansion of the given network in which the topology and parameters of the starting network change only locally, at the point where the new bus is added, allowing the rest of the system power flow solution to remain the same.

Assume that an initial n -bus network is given with all its parameters and a power flow solution. The state variables at a bus i are active and reactive power generation P_{g_i} and Q_{g_i} , active and reactive power demands P_{d_i} , Q_{d_i} (or net injection powers $P_i = P_{g_i} - P_{d_i}$ and $Q_i = Q_{g_i} - Q_{d_i}$), voltage magnitude V_i , and voltage angle δ_i (Figure 3.1 (a)). Now, suppose a new bus, number $(n + 1)$, with power demands $P_{d_{(n+1)}}$ and $Q_{d_{(n+1)}}$, is to be connected to bus i . If the power flows of the initial network are to be preserved, the equivalent power demand of bus i “seen” by the rest of the system, has to remain at the same level before and after the connection is introduced. This goal can be attained if the power demands at bus i are not considered constant (contrary to the usual situation in a real network expansion), but could vary so that the powers P_{d_i} and Q_{d_i} can conform to the changes introduced due to the new bus and the corresponding transmission line. Therefore, before the expansion, the equivalent power demands of bus i , “seen” by the system, are equal to the power demands P_{d_i} and Q_{d_i} of the starting network:

$$P_{d_i}^{equiv\ old} = P_{d_i}^{old} \quad (3.34)$$

$$Q_{d_i}^{equiv\ old} = Q_{d_i}^{old}. \quad (3.35)$$

Generally, when a new node is introduced (Figure 3.1 (b)), the existing network

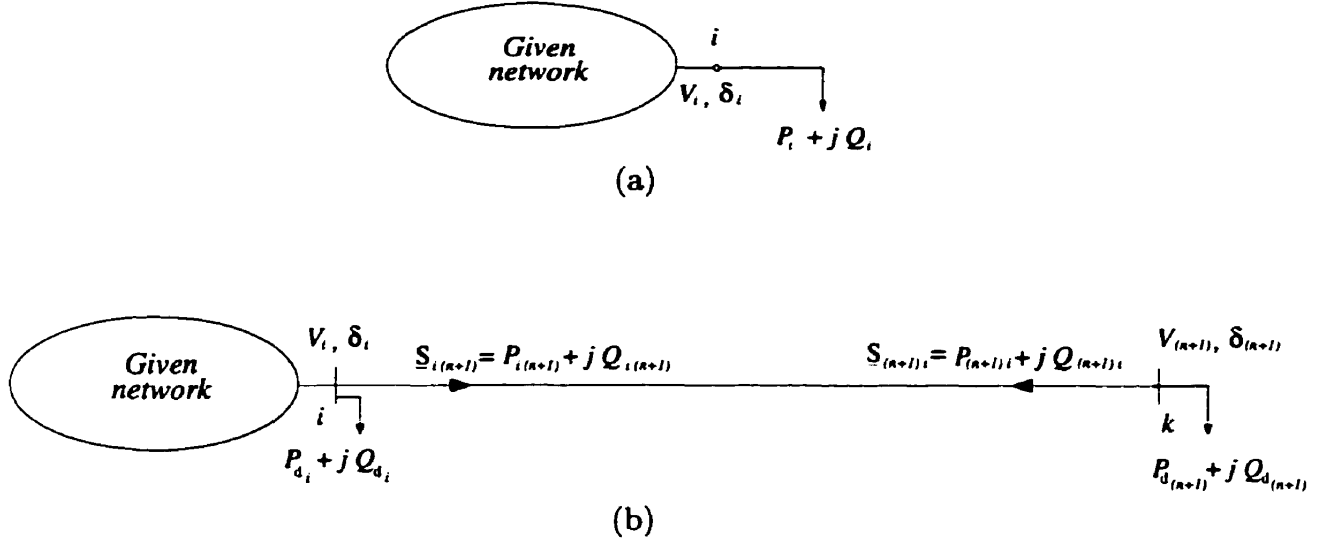


Figure 3.1: (a) Given network; (b) Network expansion.

would “feel” this addition as a change in the power “needs” at the point of connection, and in the network bus admittance matrix. For the new bus, the power demands are specified as $P_{d_{(n+1)}}$ and $Q_{d_{(n+1)}}$, while the influence of the new line may also be expressed in terms of power:

$$P_{line} = \text{real} (\underline{S}_{ik} - \underline{S}_{ki}) = R I^2 \quad (3.36)$$

$$Q_{line} = \text{imag} (\underline{S}_{ik} - \underline{S}_{ki}) \quad (3.37)$$

where P_{line} corresponds to the active power losses due to the resistivity of the new line ($P_{line} = P_{loss} = R I^2$), while Q_{line} balances the reactive power associated with the new transmission line.

Consequently, the effect of the additional bus on the given network can be

fully represented as an increase of the equivalent power demand at bus i :

$$P_{d_i}^{equiv\ new} = P_{d_i}^{old} + (P_{d_{(n+1)}} + P_{line}) \quad (3.38)$$

$$Q_{d_i}^{equiv\ new} = Q_{d_i}^{old} + (Q_{d_{(n+1)}} + Q_{line}). \quad (3.39)$$

This is very similar to the idea discussed in the DC load-flow approach, where the addition of a new load was modeled by increasing the power demand at the point of connection. However, the method based on the DC model neglected the losses and the transmission line influence, while here both effects are taken into consideration.

As previously mentioned, the objective is to keep the values of the equivalent power demands at bus i , as “seen” by the rest of the system, intact, in order to preserve the same steady state operation of the system. Accordingly:

$$S_{d_i}^{equiv\ new} = S_{d_i}^{equiv\ old}. \quad (3.40)$$

This goal can be achieved by modifying the value of the power demands at bus i , so that:

$$P_{d_i}^{new} = P_{d_i}^{old} - (P_{d_{(n+1)}} + P_{line}) \quad (3.41)$$

$$Q_{d_i}^{new} = Q_{d_i}^{old} - (Q_{d_{(n+1)}} + Q_{line}). \quad (3.42)$$

Throughout the expansion process, the original total power of the system will not change with the addition of each new bus. Instead, the power demands at a connecting bus are simply reduced to compensate for the supply of the new bus and the associated transmission line. However, additional power sources may be introduced at a deficient bus, when the available amount of power $P_{d_i}^{old}$ or $Q_{d_i}^{old}$ is not sufficient to supply the new power needs $P_{d_{(n+1)}} + P_{line}$ and/or $Q_{d_{(n+1)}} + Q_{line}$. Again, the equivalent powers $P_{d_i}^{equiv}$ and $Q_{d_i}^{equiv}$ should remain the same, while all supplementary generation has to be balanced at the very same point of generation,

by increasing the power demand of that bus:

$$P_{d_i}^{new} = P_{d_i}^{old} + P_{g_i}^{add} - P_{d_{(n+1)}} - P_{line} \quad (3.43)$$

or, in the case of the reactive power flow adjustments:

$$Q_{d_i}^{new} = Q_{d_i}^{old} + Q_{g_i}^{add} - Q_{d_{(n+1)}} - Q_{line}. \quad (3.44)$$

New active generation units may be introduced if there is no constraint that the initial total power of the system should remain unchanged. However, if this type of constraint exists, the lack of power at the connecting node may be overcome by decreasing the value of $P_{d_{(n+1)}}$, or by selecting another bus for the network expansion. Reactive power flow could generally be maintained either by introducing reactive power injection at a deficient bus, or by changing the tap ratio of the connected transformer.

The development of a network through the successive addition of new nodes would typically result in a network with a radial structure. However, in contemporary power system analysis, there is usually a need for methodologies accepting highly meshed network grids, because modern power systems are often large and have a high degree of connectivity. Therefore, having highly meshed test networks would be of a great value. Obviously, besides extending a network through the addition of new buses, there is also a need to develop a similar technique for interconnecting two existing buses to form closed loops within a network. This aim can be accomplished in a similar manner, following the very same philosophy of preserving the global operation of the given system and accommodating the necessary changes on the local level - at the points of connection. In contrast with the “radial” expansion, where the voltage is known only at the first point, and power demands are defined for the second bus, in the “loop” expansion the voltages for both connecting points are known, while the power demands at one point and the required power supply at the other end of the line need to be determined. Again, calculated power flows need to be used to modify the values of the power demands at the affected buses.

Suppose a new line is added between buses i and k in the given network (Figure 3.2). Knowing voltage magnitudes and phase angles V_i, δ_i, V_k and δ_k , together with line parameters $\underline{Z}_{ik}$ and $\underline{Y}_{ik}$, the power flows $\underline{S}_{ik}$ and $\underline{S}_{ki}$ can be calculated according to equations (2.29). If bus i behaves as a supplying bus (for $P_{ik} > 0$), the power demands have to be balanced according to (3.41) and (3.42), so that:

$$P_{d_i}^{new} = P_{d_i}^{old} - P_{ik} \quad (3.45)$$

$$Q_{d_i}^{new} = Q_{d_i}^{old} - Q_{ik}. \quad (3.46)$$

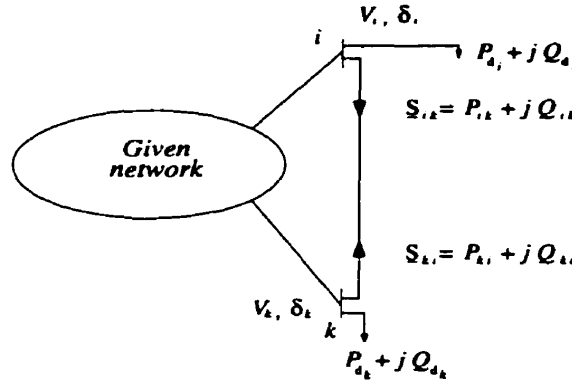


Figure 3.2: Addition of a new line between existing nodes i and k .

On the other hand, bus k consumes the transmitted power, so maintaining the equivalent powers constant would yield:

$$P_{d_k}^{new} = P_{d_k}^{old} - P_{ki} \quad (3.47)$$

$$Q_{d_k}^{new} = Q_{d_k}^{old} - Q_{ki}. \quad (3.48)$$

Recalling that active power flows are closely related to the difference between voltage phase angles, and reactive power flows are related to voltage magnitudes,

certain constraints should be imposed on how to choose the two buses to be interconnected. Namely, the values of voltage magnitude differences ($V_i - V_k$) and voltage angle differences ($\delta_i - \delta_k$) should be limited in order to avoid excessive power flows along the interconnecting lines. Also, if the “supply” bus does not have sufficient power to balance the needs of the “demand” bus, either additional generation may be introduced, or another new location for the interconnecting line may be considered.

Even though the “backwards” method does not follow the usual “natural” approach to the expansion of a given network, it permits the possibility of applying an inexpensive iterative technique, to gradually generate a power system network. It can not be used in general power system planning studies, because the approach to the problem is based on quite the opposite philosophy. Yet, the main objective is to address the problem of obtaining reasonable artificial power system networks, without the constraint that the procedure has to entirely imitate the growth of real power systems. In comparison with the “system planning” type of approach, in which each new expansion requires a new load-flow solution for the entire expanded network, the “backwards” approach allows for the problem to be solved locally. Actually, the addition of a new node (“radial connection”), as well as a new interconnecting line (“loop connection”), may each be treated as an isolated two bus problem, due to the method’s objective of maintaining the power flow solution for the original network unchanged.

Thus, once determined, the parameters of connection lines between two buses (either two existing ones, or a new bus and a given one) will remain the same throughout the whole process of network development. By maintaining the same level of power flows along the existing lines there will be no need to change the number of circuits or even the voltage level, in order to stay within the required voltage and power limits. In real power system expansions this would not be the case, because the addition of a new demand means an increase in the total system power, and this additional power must be generated globally. Therefore, it may become necessary for

some transmission lines in the existing portion of the system to be upgraded, in order to maintain the voltage drop or the thermal and stability limits.

Besides these two possible types of expansion ("radial" and "loop"), the proposed method allows for the possibility of introducing a connection between two previously defined power systems networks. This "tie-line" type connection conforms to the introduced changes in the same manner as the "loop" expansion, except that the two chosen buses are from different systems. The "tie-line" connections allow for the assembling of very large grids, potentially involving numerous combinations of previously developed power system networks.

Comparing the "planning" and "backwards" methods, it appears that they may be complementary to each other. For what is considered constant, or "stiff" in the first method, like power demands at each bus, is regarded as a "soft" parameter that accommodates the changes introduced by a network expansion in the second approach. Vice versa, the "soft" variables of the "planning" approach, such as line parameters and the power flow solution, are considered "stiff" in the "backwards" technique, and their values are not modified during the development procedure. Power generation is also treated differently. In "planning" techniques it is considered as a "soft" parameter, while in the "backwards" method, it is "semi-soft" and can be changed only under certain conditions, and in such a way that it does not influence the "equivalent" powers at any bus in the given system. Also, the first method introduces global changes in the entire network, while modifications introduced with for the second approach are only "felt" locally.

Consequently, the variables that can be influenced differ for these two methods. For the "planning" approach, power demands P_{d_i} and Q_{d_i} , and therefore the power factor $\cos \phi$ can be controlled, while this is not so for the network parameters. In the "backwards" method it is again the reverse - the network parameters of a given network are held fixed, while P_{d_i} , Q_{d_i} and $\cos \phi$ are considered "free".

Therefore, this new method could yield a feasible and economical approach to the iterative development of artificial power system networks. A complete description of the algorithm for the generation of artificial power systems, based on the “backwards” approach, is given in the next chapter. Also, sample networks and corresponding data sets will be presented in Chapter 5 and Appendix A to illustrate the scope of the proposed method.

Chapter 4

Iterative Algorithm Based on the Backwards Approach

The main idea behind the development of this iterative procedure is to successively expand the network by adding one node and/or one line after another. Accordingly, starting from a given network with a known power flow solution, the new expanded system would have one more node and/or new interconnecting line. Moreover, not only would both of the systems have feasible power flow solutions, but the updated system would maintain the same voltages and power flows over the initial part of the network. Therefore, starting from any given power system, the new network could be gradually expanded until the required size is reached, and the system obtained at each iterative step would have a feasible load-flow solution, with all voltages and line flows allocated within specified limits. Moreover, each of these networks could be regarded as suitable for a full load-flow analysis. Also, due to the backwards approach, once determined, the system parameters and load-flow solution of the existing portion of the network would not change with subsequent network updates.

Basically, with this approach to power system network development, two different sides of the problem, and thus two distinct segments of the algorithm, can be distinguished:

1. **topology module** - which consists of determining the locations of new buses and lines within the developed network, respecting the given set of constraints and topology requirements.
2. **electrical module** - where all design decisions concerning the selection of an appropriate new line and its parameters are made, as well as adjustments to accommodate the new load demands and maintain the operation of the new network within the specified voltage and power-flow limits.

Both the topology and electrical modules are interconnected, and overlap with each other in every iterative step. Which network node will be expanded, and where the new bus will be placed is determined in the first module. All the electrical requirements of the expansion are handled in the electrical module.

Aside from this classification of the nature of the algorithm's tasks, two other basic steps in power system network growth may be identified. Namely, throughout the whole discussion of the possible approaches, an assumption that a *core*, or starting network, would be somehow predetermined, was made. At this stage, it is necessary to outline how such a network may be determined. Consequently, one section of the algorithm should be dedicated to the development of the core network, which would be used afterwards, by the second section that is designed to handle further network expansion. Again, both the core generation and network expansion sections of the algorithm will consist of the previously discussed topology and electrical modules.

Also, once determined, the core network can be reused a number of times for different developments. Each time, a new, different network will be produced as an outcome, due to the random selection of connecting nodes and the random values (but within specified ranges) of certain variables.

4.1 Topology Module

As discussed in the introductory chapter, four main network layout types exist: radial, ring, mesh, and backbone. Basically, an addition of a new bus will introduce a radial type connection, while adding a new line between two existing nodes will add a loop to the system. By controlling the ratio between these two types of connections, it is possible to influence the configuration of the evolving network. Also, a general overall form for the system can be imposed by choosing either a ring or a radial type for the core network.

In addition, it would be desirable for the output network to be planar¹. The problems of planar embedding, and planarity testing of a graph are well known, and appear in different fields, such as the design of integrated circuits, the optimum single-row routing problem, and determining chemical structures. Because of widespread interest, these problems have been studied quite extensively [32].

The topology of the power system network can be regarded as a graph, with the nodes (buses) as the vertices, and the lines as the edges of the graph. In the process of selecting the location for a new node, certain parameters are introduced, and the control of their values is sufficient to avoid intersecting transmission lines. The main purpose of this part of the algorithm is to ensure planar embedding of new nodes and lines.

Methodology of Planar Embedding

For planar embedding of the network, placement of network elements has to be carefully controlled, because, while preserving the network planarity, it is also important to optimize further expandability of the developed network. In the following, the main principles of the technique of planar embedding, as applied in this algo-

¹Generally, a graph is planar if it can be drawn on a plane with no two edges crossing each other except at their end vertices.

rithm, will be outlined first. Then, an illustrative example of the potential effects that placement of the new element have on the rest of the system (only from the planar embedding perspective), will be presented.

In order to facilitate planar embedding of network elements, the plane is discretized into a grid - field of *points* (Figure 4.1), and a matrix *A_grid* of the same size as the discretized field, is introduced, with one matrix element corresponding to each point of the grid. The *A_grid* matrix could be regarded as a global grid parameter whose elements reflect the expandability of each point of the grid. Network buses are only permitted to be placed at the points of the grid, and a line connecting two nodes is only allowed to pass through these points horizontally, vertically or along the diagonal of a square. This constraint facilitates control over which points can or cannot be connected together, because their interconnection may cross a previously defined line. In addition, the maximum allowable *distance* - maximum number of grid points between two network buses, in the horizontal, vertical or diagonal direction is fixed. (Here, the value of maximal distance is set to 3.)

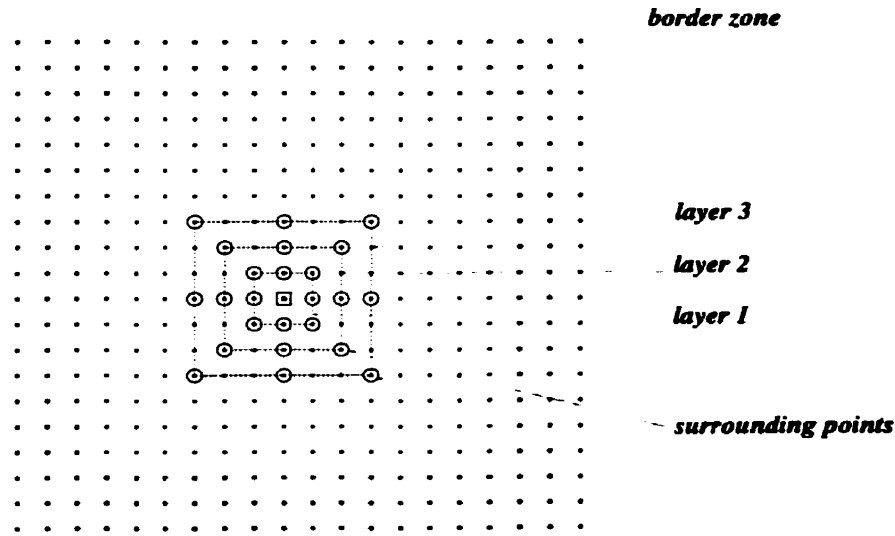


Figure 4.1: Planar grid and surrounding points of a given node.

Therefore, the generation of the network is done within a constrained space on a plane, which is discretized into a specified number of grid points, forming a uniform grid of $m \times m$ distinct points. The network bus and line placement is permitted only at the points of the grid, and is also constrained through distance and “visibility” (explained later) parameters. As illustrated in Figure 4.1, an expansion from a selected point (marked with a square) can be considered only in directions towards certain surrounding points, marked with a circle. Therefore, every grid point can “recognize” three surrounding “layers” (because the value of the maximum distance parameter is set to 3), containing 8 points each, and summing up to a maximum of 24. Only points in the border zone recognize fewer neighboring locations, depending on their distance from the edge. Furthermore, out of all the “recognizable” surrounding points, only some of them may be “vacant”, and thus “viewable” from another point, while others may be already “filled-in” - occupied by another network element or inaccessible because of the “visibility” constraints. For a global description, a variable corresponding to the number of surrounding visible “vacant” locations is associated with the each point of the mesh, forming an *A_grid* matrix of the form:

$$A_{grid} = \begin{bmatrix} 9 & 11 & 13 & 15 & \cdots & 15 & 13 & 11 & 9 \\ 11 & 14 & 16 & 18 & \cdots & 18 & 16 & 14 & 11 \\ 13 & 16 & 19 & 21 & \cdots & 21 & 19 & 16 & 13 \\ 15 & 18 & 21 & 24 & \cdots & 24 & 21 & 18 & 15 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 15 & 18 & 21 & 24 & \cdots & 24 & 21 & 18 & 15 \\ 13 & 16 & 19 & 21 & \cdots & 21 & 19 & 16 & 13 \\ 11 & 14 & 16 & 18 & \cdots & 18 & 16 & 14 & 11 \\ 9 & 11 & 13 & 15 & \cdots & 15 & 13 & 11 & 9 \end{bmatrix} \quad (4.1)$$

The *A_grid* matrix (4.1) corresponds to an empty mesh, i.e. before any step of the network development procedure has started.

In addition to the *A_grid* matrix, a set of three 3×3 matrices *AA_lay1*..., *AA_lay2*... and *AA_lay3*..., is associated with each mesh point. Each of these matrices corresponds to one of the surrounding layers, and contains information about the “visibility” of the neighboring points. Therefore, these matrices could be regarded as local grid “visibility” parameters.

The *A_grid* matrix stores information about the degrees of freedom of each point of the grid, and represents the number of surrounding points that can be “seen” and thus selected as an expansion end point (according to the defined “visibility”). The three layer matrices, *AA_lay*..., give information on which of the neighboring points can actually be seen, and which are already taken and therefore forbidden. Thus, the values of the elements in the layer matrices specify the feasible directions of an extension, and thereby define a set of possible “expansion points”. The elements of the *A_grid* matrix corresponding to this given set of possible expansion points yields the answer to which specific point should be chosen. The selection of the specific point from the given set is based on the criterion of maximal further expandability, because it will maintain the greatest flexibility of the network for future growth. This criterion corresponds to choosing a point in the outermost layer, with the largest value of the corresponding element of the *A_grid* matrix. After a new point of the grid is filled-in, associated values in both the *A_grid* matrix and the *AA_lay*... matrices are updated.

The following example is presented to illustrate the defined concept of “visibility”, and the adjustment of all required parameters affected by the network element placement. Suppose a new network is to be developed within a space of 10×10 points. Before any point is used, the 10×10 global matrix *A_grid* is of the same form as (4.1).

$$A_{grid} = \begin{bmatrix} 9 & 11 & 13 & 15 & 15 & 15 & 15 & 13 & 11 & 9 \\ 11 & 14 & 16 & 18 & 18 & 18 & 18 & 16 & 14 & 11 \\ 13 & 16 & 19 & 21 & 21 & 21 & 21 & 19 & 16 & 13 \\ 15 & 18 & 21 & 24 & 24 & 24 & 24 & 21 & 18 & 15 \\ 15 & 18 & 21 & 24 & 24 & 24 & 24 & 21 & 18 & 15 \\ 15 & 18 & 21 & 24 & 24 & 24 & 24 & 21 & 18 & 15 \\ 15 & 18 & 21 & 24 & 24 & 24 & 24 & 21 & 18 & 15 \\ 13 & 16 & 19 & 15 & 15 & 15 & 15 & 19 & 16 & 13 \\ 11 & 14 & 16 & 18 & 18 & 18 & 18 & 16 & 14 & 11 \\ 9 & 11 & 13 & 21 & 21 & 21 & 21 & 13 & 11 & 9 \end{bmatrix}$$

For a given point P (Figure 4.2), at location (i, j) of the grid, the corresponding layer matrices are of the form:

$$AA_{lay1_{ij}} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$AA_{lay2_{ij}} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

$$AA_{lay3_{ij}} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

and

$$A_{grid}(i, j) = 24$$

Because all the points that surround point P (surround in the sense defined in Figure 4.1) are “vacant” and “viewable” from P , expansion from this point could be considered towards any of the surrounding locations. Therefore, all elements in all three $AA_{lay} \dots$ matrices associated with point P , are equal to one, except for the element (2,2) which corresponds to the “visibility” of point P by itself and, therefore, is equal to zero. (A value of one in the $AA_{lay} \dots$ matrix indicates that the corresponding surrounding point is “vacant”, while a value of zero indicates that the point is “filled-in”). Since no point of the grid is yet occupied, the three layer matrices associated with the point R , at location $(i - 2, j + 3)$, are of the same form, and the element of the A_{grid} matrix which corresponds to point R has the same value as for the point P . (Both P and R do not belong to a border zone).

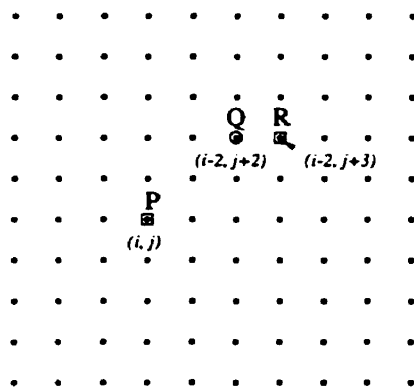


Figure 4.2: Filling-in of the grid points.

If a point Q (at location $(i - 2, j + 2)$) is selected and filled-in (Figure 4.2), the layer matrices of the two given points P (at (i, j)) and R (at $(i - 2, j + 3)$) change to:

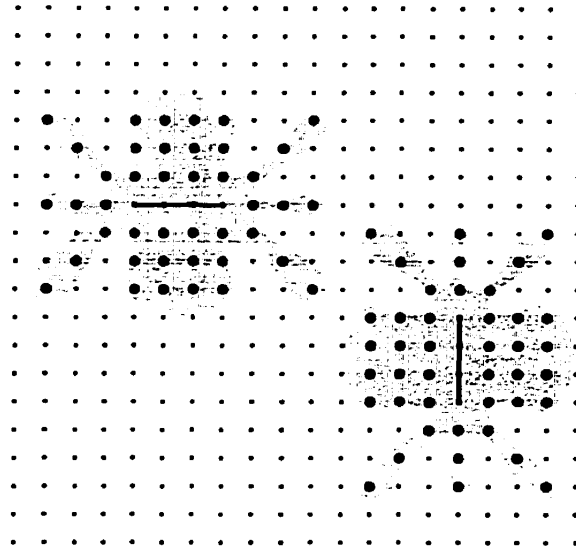
$$\begin{aligned}
AA_{lay1_{ij}} &= \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} & AA_{lay1_{(i-2)(j+3)}} &= \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \\
AA_{lay2_{ij}} &= \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} & AA_{lay2_{(i-2)(j+3)}} &= \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \\
AA_{lay3_{ij}} &= \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} & AA_{lay3_{(i-2)(j+3)}} &= \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}
\end{aligned}$$

The zero values in $AA_{lay2_{ij}}$ and $AA_{lay3_{ij}}$ indicate that an expansion from point P is not permitted in the upper-right direction, in the second and third layers. However, a point in the first layer (along that same direction) remains “vacant” and an expansion from P towards that grid point is permitted. Similarly, there is no “free” point to the right of point Q , therefore further expansion in that direction would not be possible. Also, the points P and R do not “recognize” each other, and filling-in one of these locations would not affect the another. Furthermore, the layer matrices of all points that can be “recognized” by Q (and those are the same points that can “recognize” point Q as belonging to their neighborhoods), would change in a similar way, in order to adjust the overall “visibility” of the neighborhood. Finally, the values in the A_{grid} matrix of the affected points would be modified to:

$$A_{grid} = \begin{bmatrix} 9 & 11 & \boxed{12^{(1)}} & 15 & 15 & \boxed{14^{(1)}} & 15 & 13 & \boxed{10^{(1)}} & 9 \\ 11 & 14 & 16 & \boxed{16^{(2)}} & 18 & \boxed{16^{(2)}} & 18 & \boxed{14^{(2)}} & 14 & 11 \\ 13 & 16 & 19 & 21 & \boxed{18^{(3)}} & \boxed{18^{(3)}} & \boxed{18^{(3)}} & 19 & 16 & 13 \\ 15 & 18 & \boxed{20^{(1)}} & \boxed{22^{(2)}} & \boxed{21^{(3)}} & 24 & \boxed{21^{(3)}} & \boxed{19^{(2)}} & \boxed{17^{(1)}} & 15 \\ 15 & 18 & 21 & 24 & \boxed{21^{(3)}} & \boxed{21^{(3)}} & \boxed{21^{(3)}} & 21 & 18 & 15 \\ 15 & 18 & 21 & \boxed{22^{(2)}} & 24 & \boxed{22^{(2)}} & 24 & \boxed{19^{(2)}} & 18 & 15 \\ 15 & 18 & \boxed{20^{(1)}} & 24 & 24 & \boxed{23^{(1)}} & 24 & 21 & \boxed{17^{(1)}} & 15 \\ 13 & 16 & 19 & 15 & 15 & 15 & 15 & 19 & 16 & 13 \\ 11 & 14 & 16 & 18 & 18 & 18 & 18 & 16 & 14 & 11 \\ 9 & 11 & 13 & 21 & 21 & 21 & 21 & 13 & 11 & 9 \end{bmatrix}$$

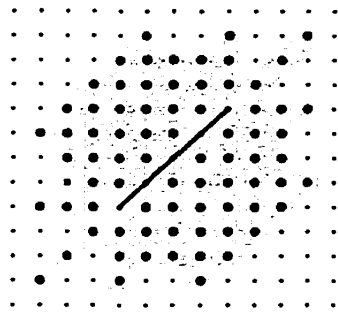
The elements affected by the “filling-in” of point Q are blocked off, while the values in brackets correspond to the reduction in the number of “degrees of freedom” associated with each point.

A connecting line between two points also changes both the layer matrices and the global matrix A_{grid} . For all three positions of the line (vertical, horizontal or diagonal), the effects of the introduced line can be treated in the same manner as previously illustrated for “filling-in” one grid point, only the process will be repeated for each grid point occupied by the newly added connection. For diagonal lines, however, an additional effect due to the line itself should be taken into consideration, because two grid points, separated by a diagonal line, become “invisible” to each other. New values at the corresponding positions of the layer matrices would mark the points that are “taken up” by the line, and therefore are no longer “vacant”, while modified values of the A_{grid} elements (of the affected points) would reflect their reduced room for further expansions. The corresponding “proximity” zones (grid points affected by a new line) for each type of line are illustrated in Figure 4.3.

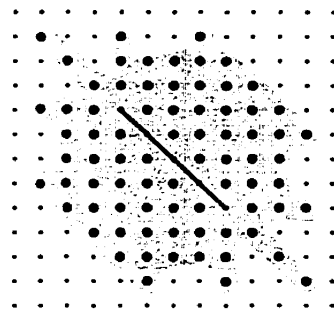


(a)

(b)



(c)



(d)

Figure 4.3: Proximity zones for each type of the line: (a) horizontal; (b) vertical; (c) and (d) diagonal.

Therefore, by introducing the layer matrices and following the above procedures that update them when a new node and/or line is added, it is possible to maintain planar power system networks. Moreover, the information stored in the *A_grid* matrix is essential for maximizing the flexibility of the developed network, to leave as much space as possible for further expansions.

Core Network Generation

The development of a core network and the extension of the core network are treated slightly differently within the topology module. For the core network, a “shape” (ring, radial, etc.) is pre-determined, and the number of “core nodes” is prescribed as an input parameter. The size of the point grid should be determined according to the total number of buses and lines required for the final network. It is advisable to match the size of the point grid with the size of the final power system network. An unnecessarily large grid would slow down the procedure and demand high storage requirements, because the size of the *A_grid* matrix is $m \times m$ (where m is a number of horizontal or vertical points of the grid), and the three 3×3 matrices, associated with each point, would yield a total of $3m^2$, 3×3 matrices. On the other hand, an undersized point grid may turn out to be quickly filled in, without allowing for a complete generation of the network. For the core network, the given system is placed in the middle of the grid. In this case, the selection of a location for each new node is not made according to the *A_grid* values, but rather by following an algorithm designed to obtain the required configuration of the core network. Also, each new bus is connected to a previously added node, not to a randomly chosen one. As an illustration, a 6-node ring network placed in a (20×20) mesh is shown in Figure 4.4. The filling-in of the grid points is due to the selected nodes and their interconnecting lines. The values of the layer matrices *AA_Lay...* and the grid matrix *A_grid* are modified accordingly, to conform to these occupied points.

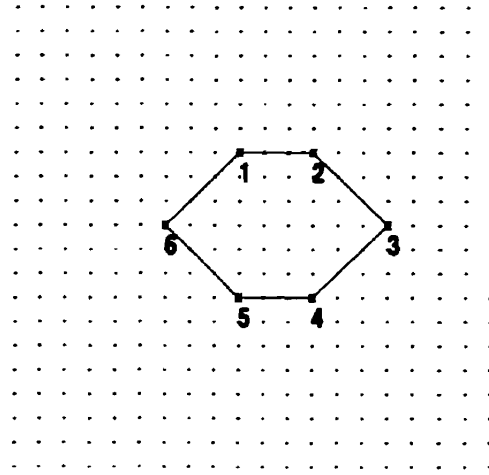


Figure 4.4: Example of a 6-node core network on a 20×20 grid.

Network Expansion

The expansion of a network can introduce either a new radial (new bus), or a new loop (new line between two existing buses) connection. For the first type of connection, the selection of a location for a new bus is based both on the “visibility” and the “expandability” of the chosen node. A flow-chart of the algorithm for the topology module operations associated with the addition of a new node is given in Figure 4.5. This procedure is executed at each iterative step, and the A_grid and all the $AA\_lay \dots$ matrices of the previous network are used as input data. The process will terminate either when a location for the new node is determined, or when there is no possibility of finding an appropriate location for the new bus. In the first case, further calculations, associated with the electrical module are continued, and the topology module overlaps with the electrical at this point. After the feasibility of the load-flow solution of this new connection is confirmed, the algorithm returns to the topology module to finally establish the new elements of the network and modify the affected entries in the A_grid and $AA\_lay \dots$ matrices accordingly. Otherwise, if a load-flow solution is not found (after a number of attempts based on different parameters for the new connection), a new expansion bus is selected. The program

terminates the network generation procedure when no further network nodes are available for expansion.

The outline of the network topology may also be controlled by two additional parameters. One regulates the maximum number of connections tied to a node, since the *connectivity* of the buses in real power systems is usually within a certain range. The other parameter defines the overall *depth* of the network expansion, or how many nodes away a new node may be connected from its “parent” node in the core network.

A new line, connecting two buses, which forms a loop connection, is treated in a similar manner. However, after the first bus for an interconnection is selected (randomly), the algorithm will not search for an “empty” space to continue the expansion, but rather for a previously selected point that is within reach (up to 3 grid point layers away), and can be selected as an end point for the new line. At this stage, the operation of the topology and electrical modules overlap. Before a second node is chosen, certain electrical properties of the proposed line must be verified. If the line does not fulfill the desired requirements, the “candidate” node for the second bus is discarded from further consideration and added to the list of nodes that cannot be connected with the current starting point. Then, another “candidate” is selected, and again verified for a possible connection. If no acceptable “candidate” exists, the first node would be considered as a *node with no loop expansions*, and a new starting node would need to be selected. In order to avoid the repeated selection of nodes with no loop expansions, such a node is transferred to a list of buses that are excluded from further consideration, for the current iterative step. The flow-chart of the topology module operations for a loop expansion is given in Figure 4.6.

As a result of managing the selection of a new bus location, and the addition of a new line by filling-in the occupied points, and modifying the corresponding layer matrices, it is possible to control in which direction and how far an extension from a given node can go without crossing any previously existing line(s). The flexibil-

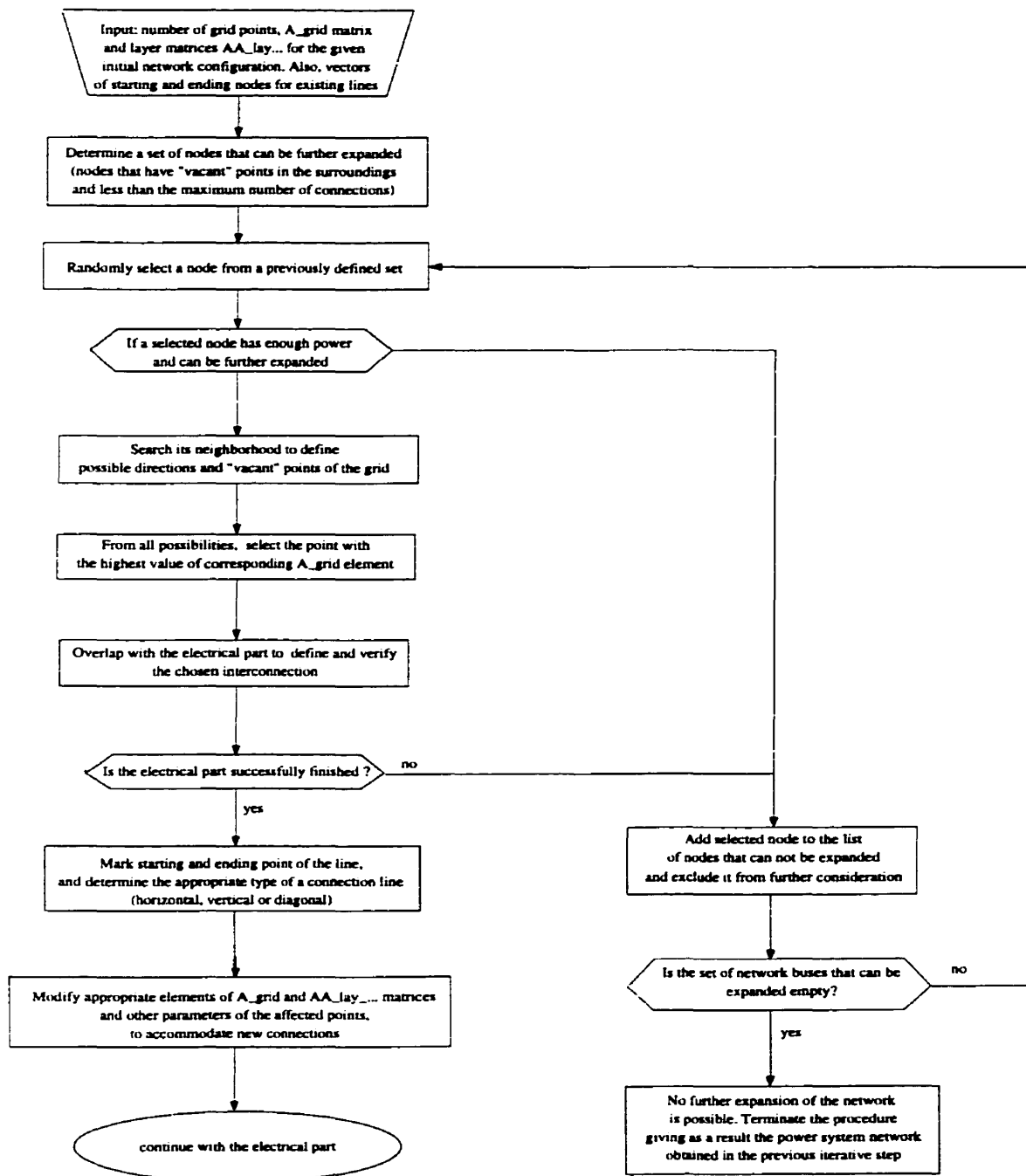


Figure 4.5: Flow-chart for a radial expansion.

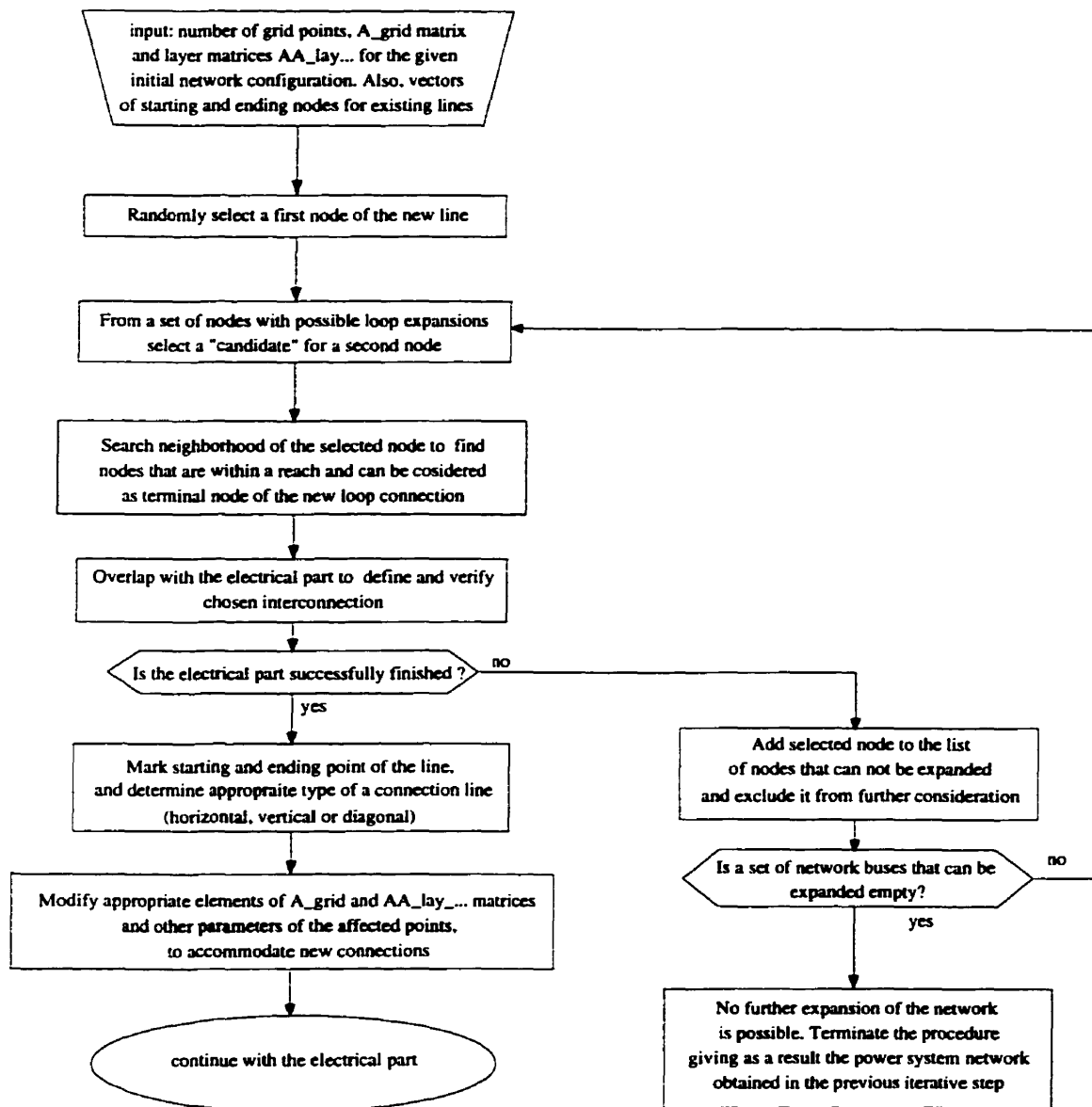


Figure 4.6: Flow-chart for a loop expansion.

ity of an enlarged network is mainly controlled through the selection of the point in the outermost layer and with the largest value of a corresponding *A_{grid}* value. Also, to some extent, the control of embedding network elements is dependent on the “connectivity” and “depth” parameters, while the overall configuration of the final output power system network is regulated through the ratio of the radial to the loop connections.

4.2 Electrical Module

A number of aspects of the problem are considered in the electrical module of the algorithm, and globally, they may be classified into four different tasks:

1. Defining the power demands and generation for each bus of the system.
2. Selecting the line design according to the power flows, and calculating all line parameters for the adopted solution.
3. Solving the load-flow for a specified system and correcting the voltage profile if necessary.
4. Adjusting the power demands and generation to accommodate the new network elements, while maintaining the power flows of the initial network unchanged.

The operation of the electrical module for core network development is different from that associated with the core network expansion. Also, the addition of a radial connection and the addition of a loop interconnection do not follow identical procedures, although both are based on the same backwards method. The differences are due to the types of required network adjustments invoked by the particular network modifications. For a loop expansion, the power implications for the two interconnected buses can be simply and directly calculated for the given bus voltages

and line parameters, while the influence of a radial expansion on an expanded node has to be found from a load-flow solution.

Prior to any electrical calculation, the topology module initiates the iterative step, as described in the previous section. After certain topology parameters of the new network elements are determined, the electrical module then proceeds to define the electrical properties of the newly added elements, and to determine the power-flow solution for the new network as a whole.

4.2.1 Specifying Power Demands and Generation

A classification of power system buses, according to the role they play in the system, was described together with the analytical formulation of the load-flow problem (Chapter 2). Basically, three different types of buses are defined - *PV*, *PQ* and the *slack bus*. From the four variables associated with each bus - net active power injection P_i (where $P_i = P_{g_i} - P_{d_i}$), net reactive power injection Q_i (where $Q_i = Q_{g_i} - Q_{d_i}$), voltage magnitude V_i , and voltage phase angle δ_i - two are prescribed, while the other two are determined from a load-flow solution. The real and reactive power demands P_{d_i} and Q_{d_i} are given for all buses. The values of real power generation P_{g_i} are generally given for all buses except the slack. Also, the voltage magnitude V_i is specified for each PV bus in the network. A summary of the prescribed and unknown (free) variables for each bus type is given in Table 4.1.

In the process of core network development, or the addition of a new radial expansion, the variables that should be known for the new bus (according to its type from Table 4.1) are defined. The specified values may be assigned either randomly (within a preset range), or by adopting certain predefined values. However, this process differs for a core network determination and a network expansion. Also, the impact of a loop and a radial connection on the network is not the same. While a

<i>bus type</i>	<i>prescribed variables</i>	<i>unknown variables</i>
PQ	P_{d_i}, Q_{d_i} $P_{g_i} = 0, Q_{g_i} = 0$	V_i, δ_i
PV	P_{d_i}, Q_{d_i} $P_{g_i} = P_{g_{sched}}, V_i$	Q_{g_i}, δ_i
slack and reference	P_{d_i}, Q_{d_i} V_i, δ_i	P_{g_i}, Q_{g_i}

Table 4.1: Prescribed and unknown variables for each bus type in a power flow problem.

radial expansion introduces a new network bus, and requires that the new active and reactive power demands be defined, a loop expansion interconnects two existing buses for which these powers are already determined. Therefore, only a modification in the node power demands (and possibly generation) is needed to accommodate the new line and its power flows.

Core Network

Generally, the initial total power demand of the system is defined for each core network, together with the number of core buses. Since this total power is actually the power that will be used for accommodating further expansions, its value should be in scale with the final size of the network to be constructed. In fact, it should be large enough to allow for the development of a new network of a desired size, because only the transmission and subtransmission levels of the power system network, and the corresponding voltages, are considered in this iterative procedure.

Therefore, active and reactive power demands P_{d_i} and Q_{d_i} are assigned to each bus of the core network, and at any moment, these overall system demands (together with the losses and required reserves) have to be satisfied with equal power

generation. Consequently, some of the system buses have to be defined as generator buses where power is injected into the system. Since generating units have physical limits of maximal, and sometimes minimal, power output, values of $P_{g_{max_i}}$, $P_{g_{min_i}}$, $Q_{g_{max_i}}$ and $Q_{g_{min_i}}$ should be assigned for each bus of this type. In order to balance the overall power demands, the maximal power generation of all buses has to be equal to or greater than the system requirements:

$$\sum P_{g_{max_i}} \geq \sum P_{d_i} + P_{loss} + P_{reserve}. \quad (4.2)$$

During the development of a core network, the power demands P_{d_i} and Q_{d_i} are associated with each bus first. Then, the total system generation is increased until the balance of the system (equation (4.2)) is met. Typically, $P_{reserve}$ corresponds to the value of maximal output of the largest generating unit, or to about 5 – 10% of the total system power demands, while estimating P_{loss} to be 5 – 10% of $\sum P_{d_i}$ is usually adequate. The real power output of each generating unit P_{g_i} is defined as a percentage of its power limit $P_{g_{max_i}}$, while its location in the network is randomly selected from the set of core buses. The generation output is specified so that $\sum_i P_{g_i} = \sum_j P_{d_j} + P_{loss}$ (with neglected $P_{reserve}$). If the parameters associated with the cost of generation are specified (as input parameters), the simplified lossless economic dispatching can be performed, to evaluate the optimal power generation.

In load-flow studies, the generator buses are *PV* buses, so the scheduled active power generation P_{g_i} , and the voltage magnitude V_i , should be specified for each bus of this type. The exception is the slack bus, where P_{g_i} is left “free” to cover the unbalanced system losses that are not known in advance. Usually, the slack and reference buses are selected as the same bus, and the voltage magnitude V_i and voltage phase angle δ_i (typically set to zero) are therefore defined.

After the generation and load demands of the core network are determined, the parameters that control the possibility of adding capacity to the system are defined. There are two of these parameters: one that globally controls the permission

to increase the total system generation, and another that controls the number of new generation locations, i.e. how many new generation buses are allowed. These two parameters would normally be defined at the very beginning of the expansion procedure, because in that case, one core network could be used a number of times for various network expansions, based on different values for the “additional generation permission” parameters.

Radial Network Expansion

Radial network expansion consists of adding a new PQ bus to the system, and connecting it (with an appropriate transmission line) to a previously existing network node. In the “backwards” approach, this type of expansion is achieved by selecting an existing bus i where the new connection will be made, and then splitting its P_{d_i} and Q_{d_i} so that a certain portion of these values can be allocated as the power demands of a new node; i.e.,

$$\begin{aligned} P_{d_{new}} &= k_p P_{d_i} \\ Q_{d_{new}} &= k_q Q_{d_i}. \end{aligned} \tag{4.3}$$

Due to the basic principle of the “backwards” approach, that the equivalent power demand of the bus selected for expansion, “seen” by the rest of the system, does not change during the expansion process, the power demands P_{d_i} and Q_{d_i} of this bus will be modified later on in the electrical part of the iterative step (after all necessary aspects of the selected radial expansion are verified).

As previously mentioned, the topology part of a radial network expansion starts first. Then, at a certain point, the electrical and topology parts of the procedure overlap, because both impose related constraints on the bus considered for expansion. The topology constraints include the number of connections that may enter or leave a given node, as well as the “vacant” spaces around the node that can be occupied by a new bus. The electrical constraint is related to the minimal power

value $P_{d_{min}}$ that may be considered reasonable for transmission at the lowest voltage level, from all given configurations.² Namely, it may be desirable to set a lower limit for the line power transfer, because in practical systems it would not be expected to use higher voltage levels for the transmission of relatively small power demands (especially at short distances), but rather lower (distribution) voltage levels. However, these distribution levels are not currently considered for the artificial power systems developed by this algorithm. Yet, there should be no difficulty to include them, if necessary, by simply expanding the predefined set of line configurations and voltages, and, eventually, by changing the value of $P_{d_{min}}$.

Based on practical experience, the value of $P_{d_{min}}$ is not unique and is not easy to define. Often, different values would probably be adopted by different engineers. Therefore, it should be noted that setting $P_{d_{min}}$ to any value, including zero, will essentially yield the same behavior of the algorithm. However, this parameter provides the possibility of setting limits for power transfer, if desired. Also, defining this value might accelerate the search process. Namely, very small power transfers at overly high voltage levels may introduce problems regarding the required voltage limits (typically set from 0.95 p.u to 1.05 p.u.), and the algorithm may not find a feasible solution among the proposed line designs, while respecting all the given limits. Normally, such an expansion would be aborted after a few attempts to correct the unsatisfied transmission constraints, through introducing relatively small variations in $P_{d_{new}}$ and/or to the length of the new line. Defining $P_{d_{min}} \neq 0$ can only accelerate the search process by reducing the search space and eliminating infeasible attempts from the beginning. On the other hand, setting a very high value for this parameter may reduce the flexibility of the expansion process.

From all the network nodes, a subset of nodes that satisfy both the topological and electrical constraints is determined, and the expansion node is randomly selected from this subset. Now, the power demands of the new bus, $P_{d_{new}}$ and $Q_{d_{new}}$, are

²As described later, the algorithm chooses one configuration from all predefined line designs.

determined according to the P_{d_i} and Q_{d_i} of the selected bus (equations (4.3)). The coefficients k_p and k_q are randomly selected from an interval of $(0, 1)$, but the value of $P_{d_{new}}$ is modified (if necessary) to be within the limits of $0.9 P_{d_i}$ (to leave some room to cover losses) and $P_{d_{min}}$. Also, instead of defining $Q_{d_{new}}$ as a portion of Q_{d_i} , its value can be selected to preserve the power factor $\cos \phi$ so that:

$$Q_{d_{new}} = \arctan(\cos \phi) P_{d_{new}}. \quad (4.4)$$

Due to the constraints imposed on certain network variables, it may happen that there are no remaining buses that can be expanded before the network is fully developed. In this case, two outcomes are possible. One is to terminate the procedure, giving as a result the power system network obtained in the previous iterative step. Another approach would be to allow the addition of new generation at one of the terminating points, or to increase the generation of one of the existing units. Which of these two approaches would be adopted depends on the values of the parameters that control the permission to add new generation into the system. In the case when the total system generation is increased, the power demand P_{d_i} of the affected bus also has to be modified to conform to the introduced change. If new generation is introduced at bus i , the net power injection P_i would not change, instead the new values of P_{d_i} and P_{g_i} would become:

$$P_{g_i}^{new} = P_{g_i}^{old} + P_{g_i}^{add} \quad (4.5)$$

$$P_{d_i}^{new} = P_{d_i}^{old} + P_{g_i}^{add}. \quad (4.6)$$

The reactive power balances are met by adjusting either the generator or the SVC's reactive power injections. However, the policy of introducing new SVCs is typically less restrictive than considering a new active power supply, because these devices are frequently used in power systems to regulate voltage stability.

New active generation is always allocated at an existing bus (never at a new bus), and if it happens to be done at a bus which was previously of PQ type, then

this bus has to be transferred to a *PV* group, and its voltage magnitude V_i must be fixed, together with its scheduled power generation $P_{g_{sched}}$. In order to preserve the same power-flow solution for the network, the value of V_i must be set to the value of the voltage magnitude at this bus determined by the load-flow calculations in the previous step.

Loop Expansion

In a loop expansion, the power flow along a line interconnecting two existing buses is not an independent variable, rather, it is closely related to the parameters of the line, and the voltages at either end of the line. From Figure 2.6, and equations (2.29)), the power flows along line ik are:

$$\begin{aligned}\underline{S}_{ik} = P_{ik} + j Q_{ik} &= \underline{V}_i \underline{I}_{ik}^* = \underline{V}_i (\underline{V}_i^* - \underline{V}_k^*) \underline{Y}_{s,ik} + \underline{V}_i \underline{V}_i^* \underline{Y}_{p,i} \\ \underline{S}_{ki} = P_{ki} + j Q_{ki} &= \underline{V}_k \underline{I}_{ki}^* = \underline{V}_k (\underline{V}_k^* - \underline{V}_i^*) \underline{Y}_{s,ik} + \underline{V}_k \underline{V}_k^* \underline{Y}_{p,k}.\end{aligned}\tag{4.7}$$

Therefore, a new loop connection would change the power at bus i by $P_{ik} + jQ_{ik}$. If $P_{ik} > 0$, bus i would behave like a supply bus, so its active power $P_{d,i}$ would decrease by the value of P_{ik} , while at bus k the active power $P_{d,k}$ would increase for the delivered value of P_{ki} . For $P_{ik} < 0$, buses i and k simply exchange roles, and the power is delivered from k to i . The same philosophy of power adjustments is also valid for reactive powers.

Recalling from previous sections, there is a strong dependence between active power flows and voltage phase angles, and also between reactive power flows and voltage magnitudes. Indeed, the relationship between δ_i and δ_k reveals the direction of the active power flow.

From (4.7), $\underline{S}_{ik}$ and $\underline{S}_{ki}$ depend on the line parameters. However, the configuration of the transmission line (defined by the voltage level, number of circuits, type of conductors as well as line parameters r, l, b), which satisfies the thermal, voltage

and stability limits, depends on the amount of power transferred over the line. An iterative procedure for determining the line design and associated parameters, adequate for the corresponding power flows calculated from (2.29), is needed, because of this feedback interdependence. The thermal, voltage drop and stability limits of the line have to be satisfied for each established connection.

Before the calculations of the electrical properties of the loop connection are performed, both connecting nodes have to be selected. The first node is selected randomly. The second node is chosen according to the topology neighborhood "visibility", while respecting the electrical constraint that the voltage phase angle difference between the two buses should not exceed 30° , as well as that the voltage drop should be within 5%. Then, potential "candidates" for the second node are divided into two groups: "supply nodes" - those that could deliver the power to the first node, and "demand nodes" - those that could consume the power delivered by the first node. Generally, the type of connection ("supply" or "demand") is determined randomly. However, if any of these subsets of "candidate" nodes is empty, the type of connection is automatically defined. Then, the second node is randomly selected from the "supply" or "demand" nodes, according to the specified type of connection. Further, if a node that plays the role of a supplier in the connection does not have enough power, there are two possible solutions: either abandon the current interconnection, or add new generating capacity. The choice depends on the values of the previously defined additional generation parameters. Normally, additional generation should be used with caution, and usually only when there is no possibility to otherwise introduce another new loop connection, and after attempts to do so were made over a number of iterations. When it is required (and permitted), the newly introduced generation should be sufficient to cover the required demands.

Knowing both points of the loop connection, the voltages $\underline{V}_i$ and $\underline{V}_k$ are defined. Then, as previously discussed, an iterative procedure is used to search for the line design configurations which respect the thermal, voltage drop and stability lim-

its for the matching power flows along the line. To illustrate the search procedure, suppose that two buses, i and k , should be connected. The power flow $\underline{S}_{ik}$, along the connecting line, will directly depend on the line parameters (as in equation (4.7)). On the other hand, the line parameters are defined by the line flows. Therefore, the iterative procedure will start from calculating the values of the power flows for each predefined line design configuration, adopting only one circuit for the established connection. If any of the transmission constraints is violated, the number of circuits is increased (by one), and the new values of the power flows are determined for this upgraded case. The iterative procedure terminates when a feasible pair of line parameters and matching power flows is determined, or once it is concluded that there is no physically realistic solution available.

Once an adequate solution for the line parameters and line flows is determined, the power demands of the affected buses are adjusted. If, after a certain number of “iterative matchings” of line parameters and power flows no adequate solution could be found, a new location for the line should be selected and tested. In some instances it will not be feasible to connect two existing buses. This is more common at the early stages of network development, when the network nodes can be scattered quite far from each other, and only few are within each other’s reach - but the existing electrical parameters and constraints do not permit their interconnection. In such cases, no loop connection is added, but the number of unsuccessful loop additions is carried forward as a parameter, to be used in the next loop expansion cycle, to indicate how many new loop lines should be added. During this “calculation and matching” procedure, the power demands of the supply buses should be continually verified, and appropriate decisions for further steps made as previously described (subsection 4.2.1 Specifying Power Demands and Generation).

4.2.2 Selecting an Appropriate Line and its Parameters

Generally, selecting an appropriate line design, including voltage level, number of circuits, compensating devices and other technical details, while respecting economical effects, is a complex task. In practice, the same type of problem is met in power system planning design. The process involves investigating a certain number of possible solutions through simplified power systems analysis. Then, according to the previously obtained results, this set is reduced to a subset of design solutions that will be considered in more detail. At this stage, more accurate methods are applied and the final decision is based on a detailed consideration of the electrical (from the point of view of load-flow, stability, reliability, short-circuit, optimal power flow and security), economical and environmental impacts. Although the procedure of planning studies might seem standardized, a number of decisions are based on experience, and would depend on the system planning engineers themselves. Because of its importance, there have been attempts to standardize the planning procedure and develop certain tools to facilitate it. Some of the methods are based mainly on the planner's expertise, while others are based on various optimization techniques (like linear programming, integer programming, dynamic programming, branch and bound). Recently, a planning tool using expert systems was developed [33]. The aim of this approach was to automate the preliminary design process of AC/DC transmission incorporating the basic knowledge and analysis tools of transmission design. The hybrid package TIDE (Transmission Intelligent Design Environment) [34] effectively combines expert system techniques and electrical power system simulation tools.

The problem of transmission system design is quite complex and generally calls for serious and extensive studies. In this thesis, however, a simplified approach was adopted, because the main purpose at this stage has been to verify the applicability of the backwards approach to the problem of synthesizing artificial power system networks, suitable for power-flow studies.

Contrary to practical studies, in which the amount of power transfer through a line is given, in the process of synthetic network development this power is not known and has to be determined. For the radial expansion procedure, when a new node with demand $P_{d_{new}} + jQ_{d_{new}}$ is added to a previously existing node i , an estimated value of the power transfer over the new line (for which the line should be designed) may be somewhat above the $P_{d_{new}}$ (about 15 – 20 %). This power is estimated differently for the development of a core network, and the loop expansion of the network. For ring core networks, the lines are designed to allow for enough power to be delivered to each of the core buses in the case of a failure in any of the core lines. In the case of radial core systems, there is no possibility to supply buses from two different points. However, when any one of the generators fail, it is important to allow for enough, or all available power (whichever is smaller), to be transferred to the loads from the rest of the system.

To illustrate the determination of these values for ring type networks, the 6-node ring network (Figure 4.7) is considered. The vectors of active power demands and generation are defined as:

$$\mathbf{P}_d = \begin{bmatrix} P_{d_1} \\ \vdots \\ \vdots \\ P_{d_6} \end{bmatrix} \quad \mathbf{P}_g = \begin{bmatrix} 0 \\ P_{g_2} \\ 0 \\ P_{g_4} \\ 0 \\ 0 \end{bmatrix} \quad (4.8)$$

Buses 2 and 4 are the generator buses. If the line 1-2 fails, there would be no power supply connected from 2 to 1 directly, rather only indirectly, through the rest of the ring. In this case, the power flows over each of the lines would be:

$$\begin{bmatrix} P_{12} \\ P_{23} \\ P_{34} \\ P_{45} \\ P_{56} \\ P_{61} \end{bmatrix} = \begin{bmatrix} 0 \\ P_{d_1} + P_{d_6} + P_{d_5} + P_{d_4} + P_{d_3} \\ P_{d_1} + P_{d_6} + P_{d_5} + P_{d_4} \\ P_{d_1} + P_{d_6} + P_{d_5} \\ P_{d_1} + P_{d_6} \\ P_{d_1} \end{bmatrix}.$$

For the failure of any other line, the power flows are similarly determined. Finally, the maximum of all the calculated line power flows is adopted as the value of the expected power flow along each line. The transmission line design is determined according to these single line failures values.

If the core network is radial type, a failure of a core line would divide the system into two islands. In some instances, the generation of each of the islands may have enough capacity to supply all demands, while in others this may not be the case. Throughout the algorithm, it can be assumed that the nearest power demands have the highest priorities. However, this assumption can be modified. Also, the outage of a generator would have an impact on the line flows, since an increase in the output power of the other generation units would be necessary to cover for the missing

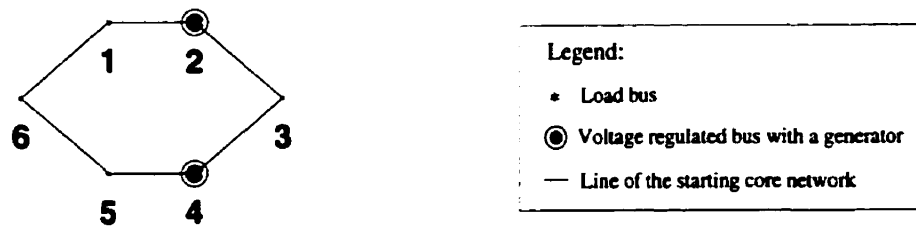


Figure 4.7: The 6-node core network.

generation. Considerations of all these possibilities yields the expected power transfer through each line as the maximal value of all the calculated power flows (regardless of the direction).

After the expected power transfer is determined, the design of an adequate transmission line should be determined for the given line length, while respecting the required constraints and properties of the previously existing portion of the network. This includes determination of the voltage level, the number of circuits and type of conductors, the transformer parameters and the type of compensation (if any).

Generally, a variety of line design solutions exist, and are applied in practical power system networks. Conductors of different sizes, mechanical and/or electrical properties are developed and used both in single and bundled configurations, and at different voltage levels. For each transmission line the particular design is selected respecting multiple criteria: starting from electrical, economical and environmental requirements, through to including different practical experiences and previously existing technical solutions. In the simplified approach adopted in this thesis, the appropriate line design is selected from a range of predefined configurations provided for each voltage level. Each configuration is described by a conductor size, number of conductors, line parameters (r , x and b), line ampacity I_{max} (or $P_{therm_{max}}$), surge impedance loading SIL, and the cost of the line.

For each given line design configuration, the number of circuits is determined respecting the thermal, voltage-drop and steady-state stability limits on the line loadability. The thermal limits bound the value of the maximum power that can be transmitted, because overheating of the lines may cause line damages and/or reduce their expected life, as well as increase the sags along the route. For a line with the expected power flow of P_{flow} , the minimum number of circuits required to satisfy the thermal limits is defined as:

$$n_{therm\ min} = \frac{P_{flow}}{P_{therm\ max}}. \quad (4.9)$$

For the voltage-drop limit, a value of 5 % (i.e. $V_r/V_s \geq 0.95$) for a heavily loaded line is usually considered as safe operating practice [20].

A third major line loadability limit is associated with the steady-state stability of the system. Namely, overly large amounts of power transferred over a transmission line may leave the system vulnerable to steady-state instability if synchronizing forces become ineffective. Generalized curves of load-carrying capabilities based on practical experience were introduced by St. Clair [35]. Further analytical verification and investigation was done by Dunlop et al. [36] and Gutman [37]. It is generally accepted that in order to ensure steady-state synchronous stability, the angles across a transmission system (the complete system from source to load) should usually be kept below 44° [38], or below $30 - 35^\circ$ across the any given line itself [20]. The maximum power transfer over a line, according to steady-state stability limits, is [20]:

$$P_{stab\ max} = \frac{V_r V_s}{B} \cos(\theta_Z - \delta) - \frac{A V_r^2}{B} \cos(\theta_Z - \theta_A) \quad (4.10)$$

where V_s and V_r are the sending-end and receiving-end voltage magnitudes respectively, δ is the phase angle difference between sending-end and receiving-end voltages, while B , A , θ_Z and θ_A are the equivalent ABCD parameters of the transmission line. Consequently, the minimal number of circuits required to satisfy the steady-state stability limits is:

$$n_{stab\ min} \geq \frac{P_{flow}}{P_{stab\ max}}. \quad (4.11)$$

Therefore, for a given power transfer P_{flow} , the minimum number of circuits satisfying both the thermal and the steady-state stability limits are determined, and the larger

value is adopted as n_{min} . Then, the value of n_{min} is verified and, if necessary, increased to satisfy the voltage-drop line-loadability limits. Also, it is common practice to use the “n-1” reliability principle when determining the final number of required circuits n_{req} .

The appropriate voltage level for the line depends on the estimated value of the power flow, P_{flow} , and the length of the line. Also, for economical reasons, the final selection should be determined based on a least cost criterion, respecting both the costs of the physical line and costs of the electrical losses. Moreover, the voltage level aspects of the previously existing portion of the network should also be taken into consideration. This is especially the case in the core network, since it is assumed that there will be only one voltage level for the entire core, and its selection is done in two iterations. The first iteration is the same as that used for a radial expansion. In the second iteration, the voltage level of the complete core network is determined to be the value which is predominant, or the “median” value. Therefore, the final decision on which voltage level and configuration should be adopted is based on evaluating all three above-mentioned criteria.

Once the voltage level and line-design configuration of the new line are adopted, the parameters of this line (r , x and b) can be calculated:

$$\begin{aligned}
 r_{newline} &= \frac{r_{config}}{n_{req}} & \text{and} & & R_{new\ line} &= r_{new\ line} \cdot \ell \\
 x_{newline} &= \frac{x_{config}}{n_{req}} & \text{and} & & X_{new\ line} &= x_{new\ line} \cdot \ell \\
 b_{newline} &= \frac{b_{config}}{n_{req}} & \text{and} & & B_{new\ line} &= b_{new\ line} \cdot \ell
 \end{aligned} \tag{4.12}$$

where $r_{new\ line}$, $x_{new\ line}$ and $b_{new\ line}$ are the parameters of the line defined per unit length, while $R_{new\ line}$, $X_{new\ line}$ and $B_{new\ line}$ are the lumped parameter values for a full line of length ℓ . These parameters are necessary for subsequent power flow

calculations.

Also, it is important to verify whether the new line would require a transformer. For that purpose, the voltage levels of the two interconnected buses are compared. Namely, as mentioned before, the addition of a new bus to the system is essentially a radial network expansion when the new bus is connected to the existing system through one new line. The sending-end of this line is the selected bus belonging to the pre-existing network, while the receiving-end is the new, additional bus. The voltage level associated with each bus is selected when the bus is added to the system, and corresponds to the voltage level of the new interconnecting line. Therefore, if the voltage levels of the two interconnected buses are not the same (either in the loop or radial connection) the new line will need a transformer. This transformer is modeled by its reactance x_{tr} (often the value of $x_{tr} = 15\%$ is adopted). The location (in which line) and the value of x_{tr} are important for load-flow analysis, therefore they should be included as part of the overall network data.

Having calculated the electrical properties of the interconnecting line, the next step is to determine the influence of the addition of this line on the affected buses. As previously mentioned, the impact of the loop expansion is simply determined from equation (2.29). For the radial expansion, however, a load-flow solution is required.

4.2.3 Power Flow Calculations

Although the power demands of the new node and the parameters of the new line are determined, the radial connection has not yet been fully defined and incorporated into the system. The next step is to verify the feasibility of the load-flow solution for the proposed expansion. The proposed addition can only be integrated into the existing network if a feasible solution exists.

Generally, it would be necessary to calculate the power flow for the entire system, including the new expansion (node and line). However, the nature of the backwards approach permits a much simplified, but equally accurate approach. Because the power injections P_i and Q_i of all the system buses are maintained constant (except for the affected bus, at which the equivalent power demand “seen” by the rest of the system is held constant) during the whole development procedure, it is possible to reduce the network load-flow analysis to one that involves only two buses: the existing bus directly affected by the expansion, and the newly added bus itself. Therefore, the required analysis actually involves only two buses and one line (Figure 4.8).

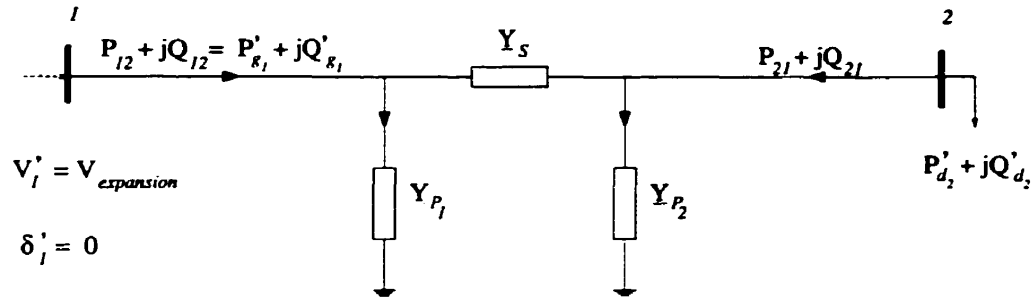


Figure 4.8: Simple two-bus system for a radial expansion.

The first bus is defined as both the slack and the reference bus in the two bus system. It is actually the expansion bus, to which the newly added line and node are connected. The expansion bus existed in the system prior to the network augmentation, therefore, its voltage magnitude $V_{expansion}$ is readily known from the previous network load-flow calculation. Therefore

$$V'_1 = V_{expansion} \quad \text{and} \quad \delta'_1 = 0 \quad (4.13)$$

Setting the value of $\delta'_1 = 0$ is justified here, because the values of the power injections depend on voltage angle differences rather than the voltage angles themselves.

Therefore, selecting any convenient value for δ_1' will not introduce any change in the solution for the power injections. Only, the value of the voltage angle δ_2' will be offset by the same amount. Although defining $\delta_1' = \delta_{\text{expansion}}$ is, theoretically, equally valid, and might seem even more “natural”, certain unexpected restrictions of the MatLab software package functions make the zero value more appropriate.³

The second node in the two-bus system is a PQ type, and its active and reactive power demands are known:

$$P_d' = P_{d_{\text{new}}} \quad \text{and} \quad Q_d' = Q_{d_{\text{new}}} \quad (4.14)$$

The power flow solution of this two-bus system yields the amount of power needed as a supply from the first bus to cover the line losses and power demands of the second bus. In other words, it shows how the existing network “sees” the addition of the new radial expansion. The solutions P_{g_1}' and Q_{g_1}' are the values required for adjusting the power demands of the affected bus so that its “equivalent” power demands (“seen” by the rest of the system) $P_{d_1}^{\text{equiv}} = P_{\text{expansion}}$ and $Q_{d_1}^{\text{equiv}} = Q_{\text{expansion}}$, as well as its voltage $V_i = V_{\text{expansion}}$, are not changed. Moreover, the values of V_2' and δ_2' (but offset by the difference between δ_1' and $\delta_{\text{expansion}}$) are the same as those that would be obtained from the power flow solution of the entire system, including the expansion. Consequently, by augmenting the load-flow solution of the existing n -bus system with the values of the power injections $P_{i_{\text{new}}}$ and $Q_{i_{\text{new}}}$, together with the values of the voltage magnitude $V_{i_{\text{new}}} = V_2'$ and phase angle $\delta_{i_{\text{new}}} = \delta_2'$, the power solution of the expanded power system network is readily attained. This approach, which avoids solving the full load-flow problem for the entire network, may

³In some cases, when the voltage phase angle was set at $\delta_1' = \delta_{\text{expansion}}$, it was not possible to find a feasible solution for the two-bus system, i.e. solution was found, but the value of the voltage phase angle of the second bus was very large, and not realistic. Although elements of the Jacobian matrix depend on the angle difference, rather than the angles themselves, the problem diminished when the value of $\delta_1' = 0$ was specified.

be both convenient and efficient, particularly for the large networks, for which the required computations may be substantially reduced.

However, this two-bus approach is only valid under certain conditions. First, a feasible load-flow solution of the two-bus system must exist. Second, the value of $P_{d_{expansion}}$ has to exceed the value of P'_{g1} . Third, the value of V_2' has to be within the specified limits, typically set to $V_{min} = 0.95$ and $V_{max} = 1.05$. Therefore, depending on the calculated values of P'_{g1} and V_2' , three different scenarios, and their corresponding procedures, are possible:

- if $P'_{g1} < P_{d_{expansion}}$ and V_2' is within the specified limits

The proposed radial network expansion can be accepted with the following values assigned to the new node $(n + 1)$ in the load-flow solution:

$$P_{d_{n+1}} = P_{d_{new}} = P'_{d_2} \quad \text{and} \quad Q_{d_{n+1}} = Q_{d_{new}} = Q'_{d_2} \quad (4.15)$$

$$P_{g_{n+1}} = 0 \quad \text{and} \quad Q_{g_{n+1}} = 0 \quad (4.16)$$

or

$$P_{i_{n+1}} = -P_{d_{new}} = -P'_{d_2} \quad \text{and} \quad Q_{i_{n+1}} = -Q_{d_{new}} = -Q'_{d_2} \quad (4.17)$$

and

$$V_{n+1} = V_2' \quad \text{and} \quad \delta_{n+1} = \delta_2' + \delta_{offset} \quad (4.18)$$

$$= \delta_2' + \delta_1' - \delta_{expanded} \quad (4.19)$$

Then, the values of P'_{g1} and Q'_{g1} would be taken into consideration in further adjustments of the power demands for the previously existing bus affected by the expansion.

- if $P'_{g1} < P_{\text{expansion}}$ and V'_2 is outside the specified limits

An SVC can be connected to the new bus in order to correct its reactive power injection and voltage magnitude, and then the power flow solution for this new improved two-bus system would be found. Due to the connected SVC, the second bus must be converted to the *PV* type. A problem arises because now both buses of the two-bus system are of the *PV* type. Moreover, it is not possible to change the type of the first bus and release some “degrees of freedom”, because the key requirement of the whole procedure is to preserve the load-flow solution of the pre-existing network. Therefore, the values of all the “equivalent” power demands and voltages must remain the same. Accordingly, the values of P'_{g1} and Q'_{g1} can not be fixed (so that the first bus becomes a *PQ* type), instead they must vary in order to accommodate the demands of the new connection. Since both buses are now of the *PV* type, their voltage magnitudes are fixed and therefore it is not possible to use the load-flow method. Rather, the solution should be based on a technique similar to the one applied for loop expansion, which requires that the voltages at both ends of the line be given, and solves for its power flows (equations (2.29)). The voltage of the first bus has to remain the same as previously found from the load-flow solution for the entire network

$$V_1'' = V_{\text{expansion}} \quad \text{and} \quad \delta_1'' = 0 \quad (4.20)$$

The main objective of this part of the algorithm is to correct the voltage magnitude of the second bus through introducing the SVC device. Typically, this means that the voltage magnitude of the second bus should be set to a certain value (e.g. V_{SVC}) and maintained constant by varying the reactive power injections of the connected SVC. In this

thesis, a simplified approach which sets V_{SVC} for every “SVC” bus to the same predefined value, regardless of the voltage magnitudes of the surrounding buses, is adopted. Methods that are more sensitive to the values of the rest of the network might be considered as possible improvements to this part for the algorithm.

Now, the voltage magnitudes at both ends of the line are given. Also, the voltage phase angle of the first bus is known. Since the equations (2.29) require that both end voltages are fully defined (V as well as δ), it remains to determine the value of the voltage phase angle of the second bus. Recalling that there is a strong coupling between active power injections and voltage angles, and given the objective to keep the active power flows over the line at a similar level before and after the correction of the voltage (i.e. to preserve the power demand of the new node $P_{d_{new}}$ as much as possible), it is adequate to keep the same value of δ_2' solved for in the previous step, based on the load-flow calculations for the two-bus system.

Therefore, the new values of P_{g1}'' and Q_{g1}'' needed for further network adjustments would correspond to the active and reactive power flows at the sending end of the line (Figure 4.9). Again, the value of P_{g1}'' must be verified for $P_{g1}'' < P_{expansion}$, and if it is satisfied, the radial network expansion can be accepted, and the following values can be assigned as the load-flow solution corresponding to the new bus:

$$P_{d_{n+1}} = P_{d_2}'' = -P_{21} \quad \text{and} \quad Q_{d_{n+1}} = Q_{d_{new}} \quad (4.21)$$

$$P_{g_{n+1}} = 0 \quad \text{and} \quad Q_{g_{n+1}} = Q_{d_{new}} + Q_{21} \quad (4.22)$$

or

$$P_{i_{n+1}} = -P_{d_2}'' \quad \text{and} \quad Q_{i_{n+1}} = Q_{21} \quad (4.23)$$

and

$$V_{n+1} = V_2'' \quad \text{and} \quad \delta_{n+1} = \delta_2'' + \delta_{offset} \quad (4.24)$$

$$= \delta_2'' + \delta_1'' - \delta_{expanded} \quad (4.25)$$

Further, this new bus should be added to the list of network *PV* buses.

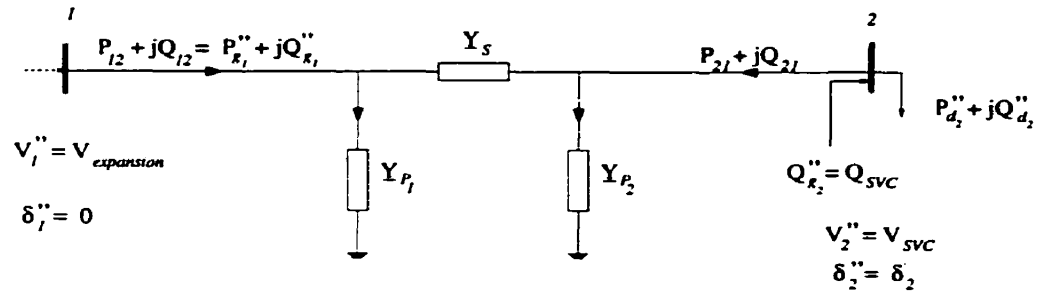


Figure 4.9: Two-bus system with an SVC at the new bus.

- if $P_{g1}' > P_{d_{expansion}}$ ($P_{g1}'' > P_{d_{expansion}}$) or the load-flow does not have a feasible solution

Certain modifications should be made: either attempts to change the parameters of the new connection ($P_{d_{new}}$ or the length of the new line) should be tried, or the addition of new generation at the expansion bus should be investigated. The second approach is valid only when a feasible solution for the load-flow exists, but the expansion bus does not have enough power to supply the required demand. Again, all the previously mentioned requirements and limits for the addition of new generation must be taken into consideration.

Finally, if after several attempts the algorithm fails to find a feasible solution for the two-bus problem, the proposed expansion would be abandoned, and another, completely new connection would be attempted.

4.2.4 Local Network Power Adjustments

The final step of the algorithm performs all the remaining adjustments to the affected bus(es) of the existing system. Since the main objective of the development procedure is to expand the given power system in such a manner that the load-flow solution for the existing network stays intact, the whole influence of the addition of a new element must be accommodated locally. Namely, the given network “sees” the new element as a change in power demand (in the case of a radial expansion), or a simultaneous change in power demand at one point and corresponding power supply at another point (loop connection). In order to preserve the existing load-flow solution and keep the power injections at all buses (except the expansion ones) unchanged, the power demands at the affected buses must be modified to account for the new values of incoming and/or outgoing power flows.

In the previous step of the algorithm, most of the necessary parameters of the connection are determined. Now it is only left to introduce the adjustments required to enable the “soft” network expansion (while keeping the pre-existing network “stiff”). These adjustments consist of decreasing and/or increasing the levels of the power demands at the points where the network expansion is performed.

The radial addition affects only one bus of the existing network. At this bus the new values of the power demands, modified to conform to the new situation, are:

$$P_{d_i}^{new} = P_{d_i}^{old} - P_{g_1}' \quad (4.26)$$

$$Q_{d_i}^{new} = Q_{d_i}^{old} - Q_{g_1}' \quad (4.27)$$

where P_{g_1}' and Q_{g_1}' are determined from the power-flow solution for the two-bus system. The same equations would be valid for the situation when an SVC is added to the new bus, except that the values of P_{g_1}'' and Q_{g_1}'' would be used (instead of P_{g_1}' and Q_{g_1}').

On the other hand, the loop expansion involves two buses of the existing network. If the connection is introduced between buses i and k , the new values of the power demands are:

$$\begin{aligned} P_{d_i}^{new} &= P_{d_i}^{old} - P_{ik} & P_{d_k}^{new} &= P_{d_k}^{old} - P_{ki} \\ Q_{d_i}^{new} &= Q_{d_i}^{old} - Q_{ik} & Q_{d_k}^{new} &= Q_{d_k}^{old} - Q_{ki} \end{aligned} \quad (4.28)$$

where P_{ik} , P_{ki} , Q_{ik} and Q_{ki} are the line flows at each end of the line calculated from (2.29).

The local adjustments of the power demands are the final part of the electrical module for both the radial and loop expansions. Before the current iteration step of the network development is fully finished, it is necessary to once again overlap with the topology part, and “draw” the new elements of the network — i.e. change the values of the *A_grid* and *AA_lay*... matrices to account for the newly used grid points.

For network expansion, the above procedure describes just one iterative step in the whole network development, which must be repeated for each new expansion (addition of a new line or a new line and a new node). Starting from the predetermined core network, the final, fully developed, power system would have a user specified number of new buses, and a corresponding number of new loop connections, determined by a user prescribed ratio between radial and loop connections. By adequate adjustment of this parameter, it is possible to generate models of highly meshed

power grids, similar to those that are often investigated in power system analysis. Each of the networks would have a feasible load-flow solution, and the parameters calculated through the development procedure would form a set of data sufficient for full power-flow studies.

4.3 Tie-Line Interconnections

In addition to the capability of fully developing new networks (starting from a given core), the proposed backwards approach offers one further feature. Namely, it enables the interconnection of two or more previously generated networks, to define even larger power system grids. The connecting “tie-lines” are treated in the very same manner as loop expansions, except that the two interconnection buses are selected from two different systems (the two that are to be interconnected) provided by the user. Again, if the specified tie-line connections comply with all the network constraints, the two systems are joined, and the existing load-flow solution for both systems is preserved. Such “tie-line” connections open up the possibility for constructing numerous combinations of previously existing networks. This approach offers an efficient method for the rapid generation of very large power system networks with feasible load-flow solutions.

Chapter 5

Artificial Power System Networks Generated with the “Backwards” Algorithm

The proposed iterative algorithm for the generation of artificial power systems, outlined in previous chapters, was expected to yield various networks of different size and topology layouts. Generated networks were targeted for load-flow studies, therefore data sets corresponding to each of the developed systems contain sufficient information for a full load flow analysis. In the proposed algorithm, implemented procedures and constraints attempted to maintain the topology and electrical features of the output networks similar to practical power systems, as much as possible. Moreover, it was ensured that the system always admitted a feasible load-flow solution. Although the objective of the outlined method was to produce load-flow test networks, it would be also possible to upgrade the applicability of the developed networks for other types of power system analysis, through the addition of supplemental network data and the enhancement of certain parts of the proposed algorithm.

5.1 Topology Layouts

The topology configuration of the network, which is mainly handled by the topology module, is characterized by the number of system buses and lines, as well as by the degree to which the system is *densely meshed* - how many loop connections (interconnecting existing buses) are present. The size of the network should be predetermined by the user, as well as the size and the shape of the starting core network. Although the iterative procedure is based on the random selection of expansion points, the global topology features of the output networks are controlled through certain parameters. Therefore, by varying the values of these parameters the user has the ability to control (to certain extent) the final appearance of the generated network. Generally, the shape and size of the starting network is expected have the largest impact on the final network topology. However, comparing different developed networks, it was observed that if the ratio between the supplemental and initial numbers of buses becomes large, this effect can fade. Furthermore, the ratio between new radial and loop expansions will also affect the final network layout, and, as will be illustrated later, it can happen that the starting core network may not be clearly distinguishable (or even it can seem to become completely hidden), if a large number of nodes is added to a relatively small core network, and if the output network is densely meshed.

In addition, the placement of the core network in the planar development grid, together with the size of this grid, can affect the network layout. Namely, if the core ring is not placed at the center of the grid, but rather near its border, the expansion of the network will be possible only in the directions where the grid exists. Moreover, by “shading” certain areas of the development grid, it could be possible to exclude them from expansion consideration, and thus further influence the shape of the final network. The “shading” or “displacement” of the development grid has not been examined within this thesis, but it may be considered in future investigations.

5.2 Electrical Parameters

The electrical parameters of the network are defined by the set of proposed pre-defined line design configurations and the set of constraints imposed on transmission limits, as well as devices and techniques applied to improve system operation.

Generally, different voltage levels with various line design configurations can be used as a basic set for network development. The line configurations implemented for the network generation in this thesis are given in Table 5.1 ([39], [40] - data for typical US overhead lines). As previously mentioned, only transmission and subtransmission voltage levels are taken into consideration, and a few configurations (out of numerous possible practical solutions) are selected. This table, however, can easily be replaced by a similar one for other voltages or line parameters, because in the algorithm these values are treated as input “lookup” parameters. Therefore, it is possible for the user to define another similar table containing a different number of possible configurations, voltage levels and parameters that are more suitable for the applications at hand.

Transmission capacity limits also play an important role in defining network parameters. Typically, three types of constraints are considered: (1) thermal, (2) voltage-drop, and (3) steady-state stability limits, and they all limit the maximal value of power that can be transmitted, based on three different aspects of transmission. Thermal limits are physical constraints defined as table values for each type of conductor, and they do not depend on system operation, nor can they be improved by some corrective technique. Voltage drop limits define the allowed voltage drop along the lines, and are usually set to $\pm 5\%$. Steady-state stability limits essentially restrain the value of the voltage phase angle difference between the sending- and receiving-end voltages of the line; these limits are mainly critical for long lines. Typically, they are limited to $30^\circ - 35^\circ$. In this thesis, both the values of $\pm 5\%$ for the voltage drop limit, and 30° for the stability limit are adopted, while thermal limits are defined in

a table, as a part of the input line data.

In addition to the power transfer constraints, a number of other line parameters (such as number of required circuits and power factor), are held within certain limits. In practical system planning studies, when the complete procedure of selecting an appropriate design is controlled by the engineer, who can directly eliminate solutions that are practically undesirable, it is not necessary to directly specify these constraints. In an automatic procedure, however, these constraints can improve the quality of the generated network, by eliminating solutions that are within power transfer limits, but do not seem to be practically acceptable for other reasons. One of these adopted limits specifies the maximum number of circuits that can be used, which impose an upper limit of 12. Then, solutions that require more circuits are not considered as feasible and are eliminated from the space of possible expansions. Another defined parameter controls the power factor. Generally, in practical systems, different compensating techniques are applied to correct the power factor or improve conditions from the perspective of the reactive power flow over the line. Since the simplified approach that involves only the application of SVCs (to address the voltage drop problem) is adopted, the parameter which limits the value of the power factor along the line is specified and set to 0.8. (In order to increase the flexibility of the program, it is possible to specify different limits for the power factor of the radial and loop expansions, because, generally, it may be more difficult to introduce a loop connection, and the potential to release this constraint may be of an interest.) Again, expansion solutions where the power factor of the transferred power is below this limit (i.e. with excessive reactive power flows) are not taken into consideration. Finally, if for any considered expansion no adequate solution can be found, a new expansion bus (or buses - in the case of loop connection) is determined.

A third group of electrical constraints pertain to the possible introduction of additional generation into the network, when needed. These limits specify whether new generation can be added and, if allowed, how many new generating locations are

permitted within a developed network.

Typically, all the above-mentioned constraints will have, as expected, a strong impact on the electrical parameters of the developed power system, and further, they will also impact on the topology layout of the network. These effects relate to enhancing or restricting the possibility of the network to expand in certain areas or in certain manners (allowing no radial or loop expansions), causing the procedure to terminate before all desired new network elements are placed. The network generated by the “halted” procedure will be suitable for load-flow studies (having defined all the necessary parameters defined, and a feasible load-flow solution), but it will not be the desired network with either the specified number of nodes, or the desired mesh density. One example of the impact that electrical constraints could have on network topology is illustrated later, with two networks that have the same starting ring core network, the same number of specified additional buses and the same ratio between loop and radial expansions, but have different parameters for the permitted additional generation. When the additional generation was unlimited, the new network was developed in full, while for the limited new generation output, it was not possible to successfully add all the desired loop expansions.

Line Configurations

For each line of the network, the specific line design is chosen from the set of given configurations (Table 5.1). Here, only six possible solutions (from the large variety applied in practice) are considered: 2 for 735 kV, 2 for 500 kV and 2 for 345 kV voltage levels. The corresponding data, needed for the network models and load-flow calculations, are given for each configuration. They describe:

- voltage level V (kV)
- line resistance r ($m\Omega/km$)
- line reactance x ($m\Omega/km$)

- line shunt susceptance b ($\mu S/km$)
- characteristic line impedance Z_0 (Ω)
- surge impedance loading of the line SIL (MW)
- thermal limit of the line I_{max} (A)
- number of circuits in a bundle
- cost of the line (M\$/km)
- terminal cost of the line (M\$/line)

The data used in this thesis are based on common US practice ([39], [40]), appropriate for a system frequency of 60 Hz. However, this data set can easily be either expanded with additional configurations, or completely replaced by another set preferred by the user. For example, data for a system frequency of 50 Hz, appropriate for Europe or Japan, could be applied instead.

Transformer and SVC Data

Aside from the line parameters, transformer data are also needed for proper network modeling. All transformers are assumed to operate at nominal turns ratios (i.e. $t = 1 p.u.$), with the transformer reactance set to $x_{tr} = 15\%$ for each transformer at each voltage level, while their resistances are neglected. The specifications for the transformers applied in the algorithm are given in Table 5.2.

In practice, transformers can be used as regulating devices. However, in this simplified approach, their regulatory role is not considered, but it could be included through further improvements of the “knowledge-based” part of the algorithm.

Regulation of voltage profile is done through the application of SVCs. It has been assumed that these devices can be connected to any bus, whenever needed to provide a desired voltage profile. Also, their capacities have not been limited

Voltage level (kV)	Number of cond.	r ($m\Omega/km$)	x ($m\Omega/km$)	b ($\mu S/km$)	SIL (MW)	I_{max} (A)	Line cost (M\$/km)	Terminal cost (M\$)
345	1	45.2174	475.8385	3.3867	318	1450	0.2385	1.44
345	2	30.4037	372.7950	4.3253	405	2094	0.2981	1.44
500	2	18.6025	386.5217	4.1742	822	2800	0.3578	2.4
500	4	27.7950	327.8261	4.8792	965	2884	0.5366	2.4
735	3	15.0725	369.5652	4.3073	1844	4350	0.6559	4.2
735	4	12.5000	349.1925	4.5704	1955	4748	0.8199	4.2

Table 5.1: Line Specifications [39], [40].

Rated Voltage (kV)	Rated Power (MVA)	Reactance (%)
345	600	0.15
500	1100	0.15
735	1650	0.15

Table 5.2: Transformer Specifications

throughout the procedure of network development. In this manner it was ensured that at each iterative step, the load flow solution of the network developed at the previous step would be preserved. The limits of Q_{min} and Q_{max} are defined for each SVC connected to the system only at the very end of the network generation.

5.3 Ring Core Networks

Prior to the procedure of network expansion, the starting core networks have to be developed. The illustrative samples of power systems were generated from ring core networks having six and thirty buses.

In the core networks, load demand is determined for each bus, while generators are placed randomly, and additional SVCs are placed where necessary to support the voltage stability of the system. Total output power of the generating units must be sufficient to meet load demands and losses. (The reserve requirements are not considered). If further network development does not allow addition of new generating units, then the total system generation is scheduled at the ring, and its value should be large enough to allow the desired size of the final output power system network. In each core network, all lines are specified at the same voltage level. Also, the lines

are selected in such a way, that, in the case of failure of any one of them, the rest of the system will be able to support all the required power transmission.

5.4 Example Networks

Various artificial power systems can be developed starting from the predetermined core networks, and applying “backwards” iterative method for network generation. Generally, there is no upper limit on the size of the new network, but in order to successfully develop large and/or densely meshed systems, it is most efficient to select the core network of the appropriate size (both from the perspective of number of buses and total system power), and to set adequate values for the previously discussed control parameters, so that sufficient flexibility in both the starting and developing network is maintained.

To evaluate the behavior of the proposed algorithm, various test were performed, with different starting core networks, different numbers of additional nodes and different mesh densities. For these tests, the algorithm successfully generated networks that have a feasible load-flow solution. Also, throughout the expansion procedure, the load-flow solution (line flows and voltages) of the network developed in the previous iterative step, has been examined and shown to remain intact. Therefore, the ideas on implementing the iterative method with the “backwards” approach, with respect to “flexible” and “stiff” variables (as discussed in 3.5) appears to be feasible and to give good results.

Experiments with different values of the control parameters (mesh density or potential to add new generation) revealed their influence on the output network. In some cases limits imposed by those parameters were so strict, that they prohibited the full development of the desired network. Also, values of these parameters can significantly influence the time needed to develop the specified power system.

To illustrate the proposed concept of network development, examples of relatively smaller systems are presented in this chapter. The topology layouts and data sets for larger generated power system networks are given in Appendix A.

First, an example of the 66-bus network, with eighty six lines is presented. It was developed from the 6-node ring core network through the iterative addition of sixty buses. The mesh density requirements were not set to a high value - every new loop connection is added after three new radial expansions are successfully placed. The resulting network layout is shown in Figure 5.1. The corresponding line data, as well as PV and PQ bus data, and the load-flow solution are given in Appendix A

For this example, the addition of new generating units was not limited, and the power factor for transmission lines was restricted to minimum value of $\cos\varphi = 0.8$, for both loop and radial connections. The algorithm developed the full size network - all the required new buses and lines were successfully added. Also, all three line loadability limits (thermal, voltage drop and steady-state stability) were satisfied for each line.

In order to demonstrate the influence of the control parameters which specify the mesh density, generation addition and/or power factor limits, two other networks are presented. Both of these networks were developed from the same 6-bus starting ring core network through the addition of sixty new buses. Also, for both networks the mesh density was specified at a relatively high value, requiring that a new loop expansion should be added after each new radial connection is successfully placed. The additional generation parameters were set to different values for these two networks.

For the network given in Figure 5.2 the addition of new generation was not limited. The resulting network was developed nearly complete, having sixty six buses and one hundred and twenty four lines (out of one hundred and twenty six required). The increase in the mesh density parameter resulted in a highly meshed network, which is often interesting for testing the performance of load flow algorithms. Cor-

responding data sets (for lines, PV and PQ buses) and the load flow solution of this network are given in Appendix A.

In the case of Figure 5.3, no possibility of adding new generation sites was permitted. This resulted in a network with the same number of buses, but with fewer lines. Thus, the limit of new generation disabled the growth of a fully developed network (with all required buses and lines). The line and bus data, as well as load flow solution for this system are given in Appendix A.

In addition to investigating the influence of those control parameters on the

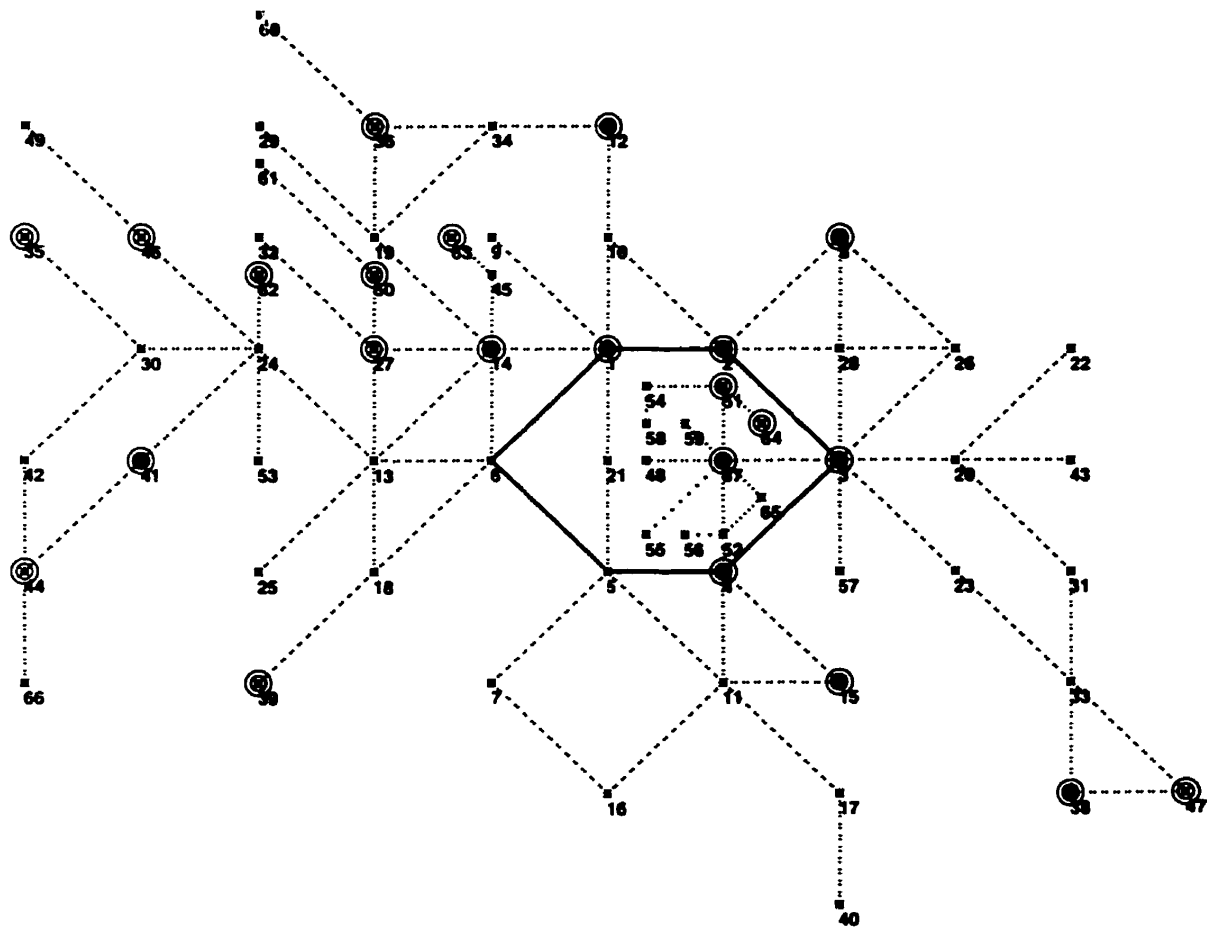


Figure 5.1: A 66-bus network with 86 lines.

size of the output networks, other parameters of the developed networks could be observed. Generally, the proposed algorithm for network expansion tried to implement realistic parameters for line design and commonly used techniques, in order to attempt the development of networks with topology layouts and parameters that are within the range expected for practical power system networks. For each line the active transferred power was below the thermal and steady-state stability limit, and the excessive flow of reactive power was limited by the control parameter which specified the minimum value of the line-flow power factor. Also, in the power flow solution,

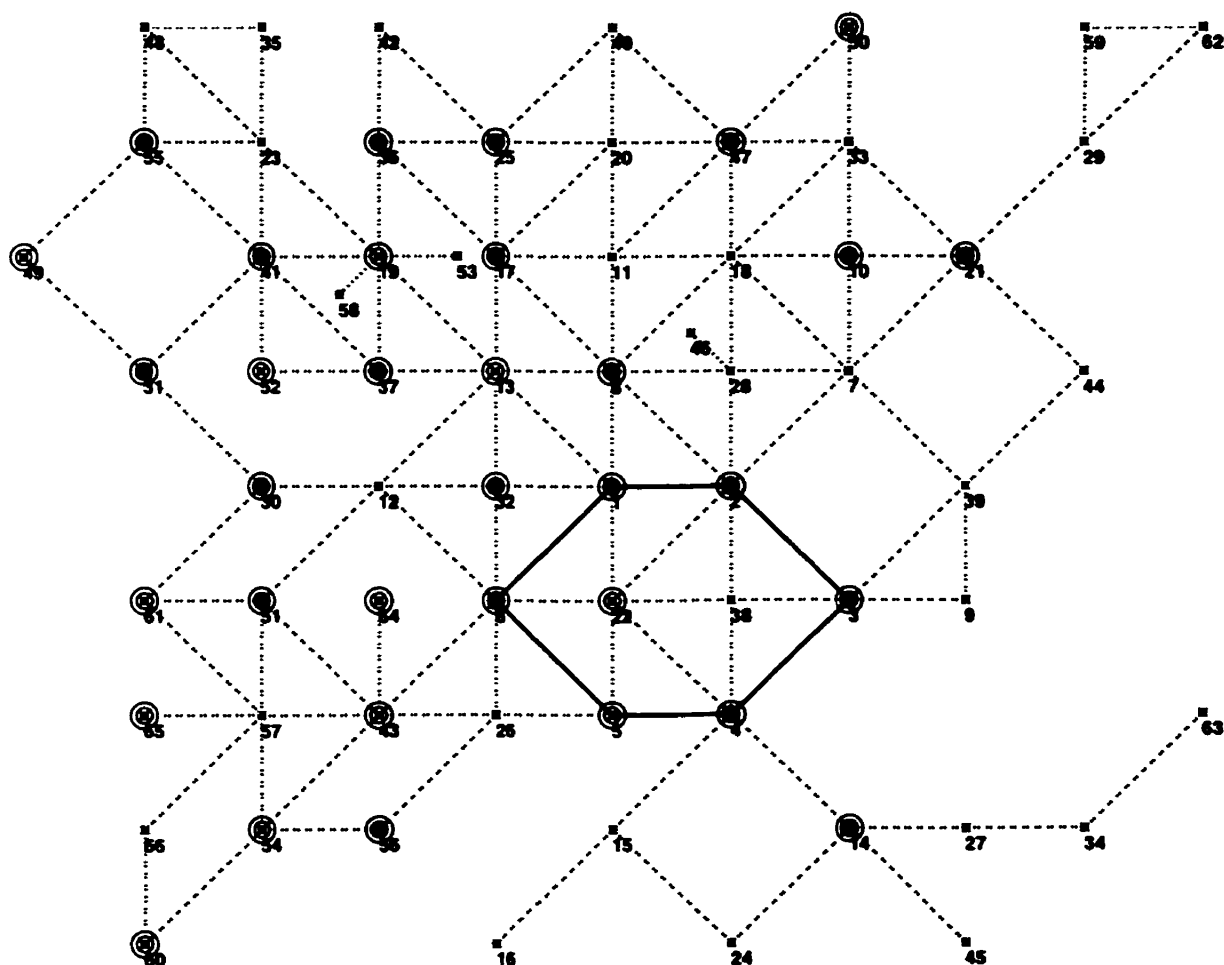


Figure 5.2: A 66-bus network with 124 lines.

the voltage magnitudes at all buses were maintained between 0.95 and 1.05 p.u. This was attained by the application of SVCs at buses where voltages were outside these limits, in which case the affected bus become of a PV type.

The unrestricted addition of new generation sites and the necessary SVCs could lead to a quite large number of regulated PV buses, as seen in the second example (Figure 5.2), in which the mesh density requirements were high and there were

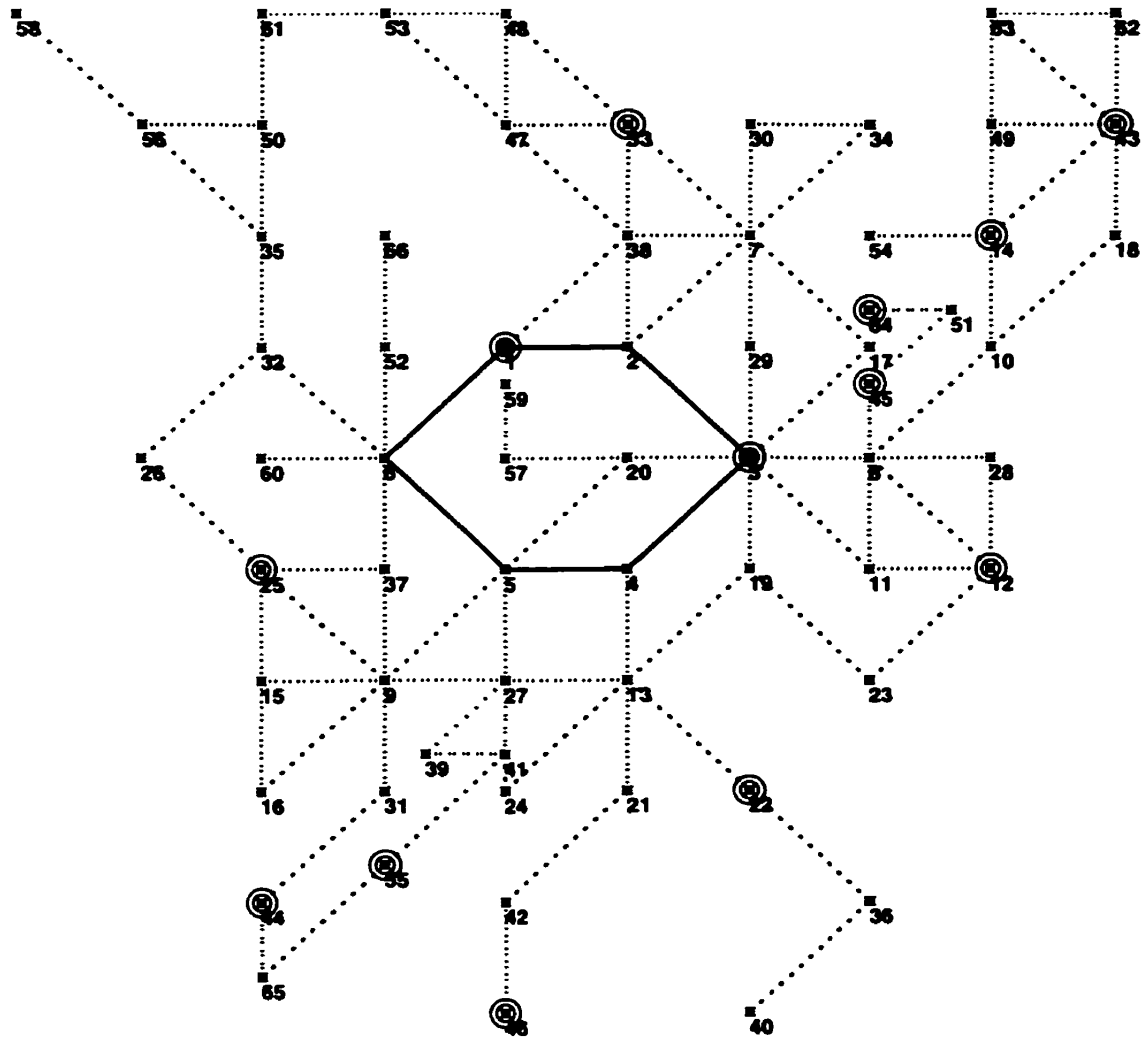


Figure 5.3: A 66-bus network with 97 lines.

no restrictions on adding new generation. On the other hand, PV buses in two other examples, as well as in the large network of 330 buses given in the Appendix A, were not so numerous. Although such a high ratio of PV buses is not typical in common vertically integrated power systems, under the newly proposed “open access” operation, and with the presence of larger numbers of relatively small, but more efficient and economical generation units, these types of artificial power system networks may be of an interest. On the other hand, by imposing limits on the number of new generation sites, and by increasing the value of required power factor, development of such networks can be avoided.

Therefore, through varying the values of introduced control parameters, it is possible to generate different power networks, with various size and topology features. Moreover, as expected, these control parameters also influence the electrical parameters of the generated networks. The possibility to modify the values of the limits imposed by the control parameters provides the flexibility to develop various networks of a different scope.

Also, due to the simplified approach adopted for line compensation (only SVCs were considered to correct the voltage profile), it was not always possible to maintain the values of reactive power demand and/or generation within the desired values, since the power demand of the expanded bus compensates for both the demand of the new, additional, bus and the power dissipated in the new line. However, this problem could be addressed through the application of more sophisticated methods for line compensation. For now, some adjustments of reactive power demand Q_{d_i} and/or generation Q_{g_i} could be done at affected buses, but without changing the overall reactive power injection Q_i at that bus. Further, application of additional SVCs could be considered, if necessary.

All generated networks are developed to have a feasible load-flow solution, for the certain specified power generation and demand. However, it was observed that

even when the variation in power demands of certain buses was introduced, the power flow solution of the developed network still existed. The performed investigation was not extensive, and more detailed experiments could be suggested as a future work.

In addition to the previously discussed example networks, one network obtained through the interconnection of a set of previously developed smaller systems, is presented to illustrate the proposed *tie-line connections*. This technique enables the interconnection of previously developed networks into a larger power systems through the addition of connections similar to tie-lines. The size of the “element” networks in this example is relatively small, since the main objective is to illustrate the implementation of the proposed tie-line connection concept, rather than to present very large networks.

The time needed to develop the 66-bus network with relatively low mesh density was about 3-4 hours; for highly meshed networks it was about 10 hours, while for the large 330-bus system (with moderate mesh density) it was in the range of 2-3 days (on a Sparc Ultra workstation). It should be noted that the required time depends not only on the size of the required network, but also on the values of control parameters, as well as on the process of node selection.

The topology layouts and all the corresponding data sets, together with the load-flow solutions, for all the illustrative examples, and samples of the larger networks are given in Appendix A. As previously mentioned, the largest of these networks does not present the upper limit on the size of the networks that may be generated by this algorithm. They have been chosen to demonstrate the possibilities of the algorithm and to illustrate the effects of the parameters on the output networks.

5.5 Conclusions and Future Work

The lack of numerous, large, and generally accessible power system networks, suitable for load-flow analysis, as well as the general absence of procedures to obtain such power systems (except the work by Javidi, McFee and Galiana [18]), was the main motivation for this work. The example power system networks developed by the proposed iterative “backwards” algorithm show that the established procedure can yield such artificial systems. The proposed algorithm enabled the generation of test networks of arbitrary size and connectivity, possessing the features associated with real power grids.

The outlined method was based on an iterative approach, starting from a given core network, to develop a required power system through the addition of a radial (new bus and a corresponding line) or a loop (line interconnecting existing buses) connection at each iterative step. As discussed in Chapter 3, different methods could be considered to incorporate this new element into the given system. The technique proposed in this thesis is based on the objective to maintain the network determined in the previous iterative step intact everywhere, but at the bus (or buses) where the new connection is introduced. This new approach could be regarded as quite the opposite to the techniques usually applied in power system planning. In the planning studies, the main problem is to expand the existing power network not only from a topology perspective, but also from the point of view of total power system demand, by increasing the overall system demand and generation to account for the power of an added bus. The algorithm for the development of artificial power system networks, however, does not, necessarily, have to address the problem of the increased power system demand, but only to investigate the topology expansion (together with assigning a fractional power to the new bus), while maintaining the required system parameters and constraints. Thus, the approach that the power delivered to the new bus, and/or a power flow in a new line, is accommodated by a modification

in the power demands and/or possibly generation at a point of connection seemed attractive, because it allowed the complete previously developed network to remain the same. The addition of the new element has no impact on any other part of the system, except at the bus (or buses) of connection. All previously determined power flows and voltages remain the same, and the addition of the new connection does not call for verifying whether the existing system needs some upgrading to withstand the network expansion.

The proposed algorithm has two parts. In the first part a core network (of the size specified by a user) is assembled. In the second part, starting from the given core network, further network expansion is accomplished by adding one bus after another, or a new line between existing buses, until the desired network configuration is attained. The first and second parts of the algorithm are decoupled, allowing the user to alter solutions adopted for the core network, and to improve the voltage profile through the addition of SVCs. (In the second part, addition of SVCs is incorporated in the development procedure, and does not require any user's interaction.)

In addition, both the first and second parts consist of two modules - topology and electrical, and they overlap in each part. The topology module determines where, in the existing network, a new element can be placed, and updates the necessary topology parameters. The expansion point is selected randomly from the set of buses that could be considered for the specified expansion, but, when possible, the placement of the new bus is done in such a way that the flexibility of the network for future expansions is maximized.

The electrical module addresses all problems regarding the electrical parameters of the network. In addition to the goal to evolve artificial power systems that have a feasible load-flow solution, it was intended that the generated network should resemble the practical power system as much as possible. Also, the goal was to develop an automated procedure that would not require user interaction at each iterative

step. To obtain networks that have characteristics similar to practical power systems, the same or similar design parameters and system constraints were implemented. To enable the automated network growth, the iterative “backwards” method was introduced and combined with an approach similar to the “knowledge-based” methods usually considered in expert systems for automatic preliminary power system design and planning studies. Namely, in the last 10-15 years, a number of expert system tools were developed to incorporate various power system analysis and practical knowledge used in the planning studies ([34], [33]). The scope of these analyses is broad, and includes not only power flow analyses, but stability, security and other aspects needed to be considered and typically applied in practical studies, when the addition of the new line is planned. However, the method applied in this thesis is less extensive than the expert system tools. It is based on line loadability limits, load-flow and least-cost analysis. Therefore, the line configuration of each line is selected from the set of possible design solutions, and the power flow in each line satisfies the thermal, voltage-drop and steady-state stability limits. The final decision on which particular configuration should be adopted is based on the least-cost analysis, as well as on the voltage level and line design configuration of the pre-existing part of the network.

Lines and other system devices are modeled in compliance with the standard network equivalent circuit models typically applied in load-flow studies. Also, certain control parameters are introduced in addition to the line loadability limits, to model system characteristics like connectivity, power factor, number of circuits or possibility to introduce new generation sites. These additional parameters could not be incorporated into the standard models, but they influence parameters of the output networks and give an important possibility to automatically generate networks that are more similar to the practical power system networks¹. Since the values of these

¹Even with the implementation of expert system tools, practical evaluation and planning studies are usually done in few stages, with the final evaluation and decision made by an engineer. However, in the automatic procedure (necessary for the generation of artificial power systems), the final decision is made by the algorithm itself, and there is no interaction with the user to allow elimination of undesirable (although feasible), or improvement of, selected solutions.

control parameters can strongly affect the final power system network, it is important to specify them in such a way that the limits which they impose are sufficiently strict to ensure quite realistic output networks, but not too tight so that they overly reduce the flexibility to fully develop the desired power system networks.

Although the method applied for the electrical part of the algorithm was simplified in comparison to the complete real procedure, the generated networks showed that the proposed “backwards” approach enables the generation of artificial load flow test networks with the required system parameters. Moreover, the analysis of intermediate results confirmed that the network developed at the previous iterative step remained intact, with the same power flows and bus voltages. The only change was observed, as expected, at the load demands and /or generation of the bus (or buses) affected by the new connection. Also, every “intermediate” network (developed at each iterative step) had a feasible load-flow solution and satisfied the required system parameters, and could be equally used as test network. Furthermore, even for certain changes in power demands, the developed network had a feasible power flow solution.

Generally, large and densely meshed networks are considered more interesting as load-flow test networks. In addition to the ability to develop such networks through the iterative procedure, the proposed method enables the generation of large networks by the interconnection of previously developed ones through one or more tie-lines. Such combinations could be done in numerous ways, allowing a user to assemble large power grids. This “tie-line procedure” can be implemented both on the networks that were results of either iterative expansion, or previously applied tie-line interconnections.

Finally, all the developed power system networks could be added to a “library” of existing systems and sorted according to their size or certain parameter values. Each of these networks could then be used either on its own, or as the “element” in the process of tie-line interconnection network assembly.

Future work

The main objective of this work was to investigate the possibility of developing artificial power system load-flow test networks through the implementation of an iterative “backwards” approach. Certain simplifications were introduced in order to examine the proposed method. Since the obtained networks demonstrated the applicability of the proposed method even with the simplified procedures, further improvements in the electrical module, such as more sophisticated techniques for line compensation, application of transformers with off-nominal turns ratios, or even incorporation of expert system programs (like TIDE [34]), may improve the output networks and increase their applicability to other areas of power system analysis (such as reliability, economic dispatch, unit commitment, etc). The implementation of additional network parameters for models typically used in considered power system studies would also be necessary to expand the usability of the developed power system networks.

In the topology module, experiments with the exclusion of certain areas from the expansion space, or placement of the core network at the edge of the planar development grid could be interesting, indicating whether network layouts could be more actively controlled.

Finally, the generation of other configurations of core networks, as well as the development of other new test power systems and adding them to the library of existing networks, would enhance the results achieved with the new “backwards” approach.

Appendix A

Samples of Generated Artificial Power System Networks

To illustrate the behavior of the proposed “backwards” approach, a selection of the developed artificial load-flow test networks are included. First, three networks of 66 buses, discussed in Chapter 5, are introduced. Then a network which demonstrates the implementation of tie-line connections to interconnect smaller, previously developed networks, into a larger power systems, is given. Finally, a larger network of 330 buses is presented.

Topology layouts and adequate data sets are included for each of the networks. In the first topology layout presentation, the initial ring core network and the extended portion of the network could be distinguished; also, the bus numbers are indicated. In the second layout, all the network lines are equal, and the emphasis is on the overall topology layout, which sometimes, in the first type of presentation, is difficult to identify for larger networks. The legend for the first type of layout is given in Figure A.1(a), and for the second one in Figure A.1(b).

Also, for each developed network the line data, PQ and PV bus data, and load-flow solution are given in the following five types of tables:

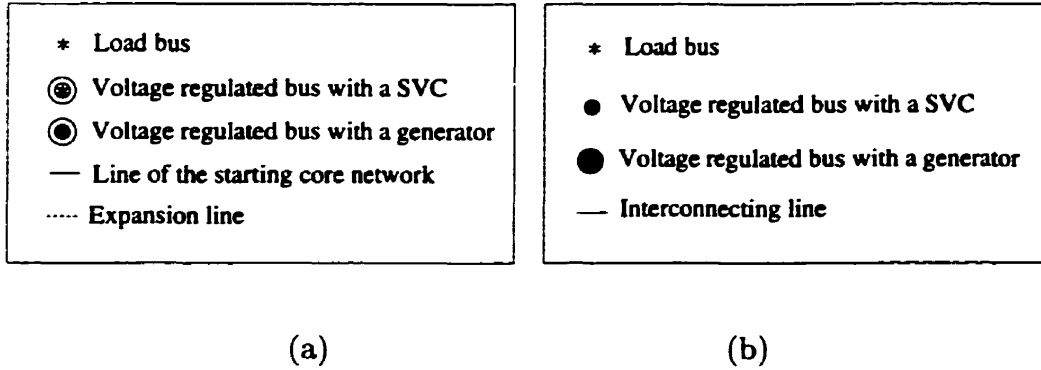


Figure A.1: Legend for network topology presentations .

• **line data table** specifying:

- * line number
- * line terminals (sending and receiving end buses)
- * selected voltage level (kV)
- * number of circuits
- * line resistance R (Ω)*
- * line impedance X (Ω)*
- * line susceptance B (mS)*
- * transformer impedance X_{tr} (Ω)
- * thermal line limit I_{max} (A)
- * length of the line (km)

• **PV bus data** giving for each PV bus:

- * bus number
- * value of voltage magnitude V ($p.u.$)
- * maximum value of active power generation P_{gmax} (MW)
- * maximum value of reactive power generation Q_{gmax} ($MVar$)
- * minimum value of reactive power generation Q_{gmin} ($MVar$)
- * scheduled active power generation P_g (MW)
- * active power demand P_d (MW)

*The given values are calculated equivalent values for a specified number of circuits

- * reactive power demand Q_d (MVA_r)
- **PQ bus data** specifying for each PQ bus:
 - * bus number
 - * active power demand P_d (MW)
 - * reactive power demand Q_d (MVA_r)
- **load-flow solution - bus data** specifying for each bus:
 - * bus number
 - * active power generation P_g (MW)
 - * reactive power generation Q_g (MVA_r)
 - * active power demand P_d (MW)
 - * reactive power demand Q_d (MVA_r)
 - * voltage magnitude V ($p.u.$)
 - * voltage phase angle δ (rad)
- **load-flow solution - line data** showing for each line:
 - * line number
 - * active power flow P_{flow} (MW)
 - * reactive power flow Q_{flow} (MVA_r)
 - * surge impedance load SIL (MW)
 - * ratio between active power flow P_{flow} and surge impedance load SIL
 - * ratio between active power flow P_{flow} and maximum power limited by the steady-state stability $P_{max,stab}$
 - * ratio between current flow I_{flow} and specified thermal limit I_{max}

As previously mentioned, the provided networks are only illustrative examples, and do not represent the largest ones that the algorithm could generate.

A.1 A 66-bus Network with 86 lines

This network was developed from a 6-bus core ring network, through the addition of sixty new buses. The mesh density requirements were specified at moderate level, requiring that a new loop connection was attempted after three new radial connections were placed. A number of new generation sites was not limited. The generated network was developed in full, having all the desired buses and lines.

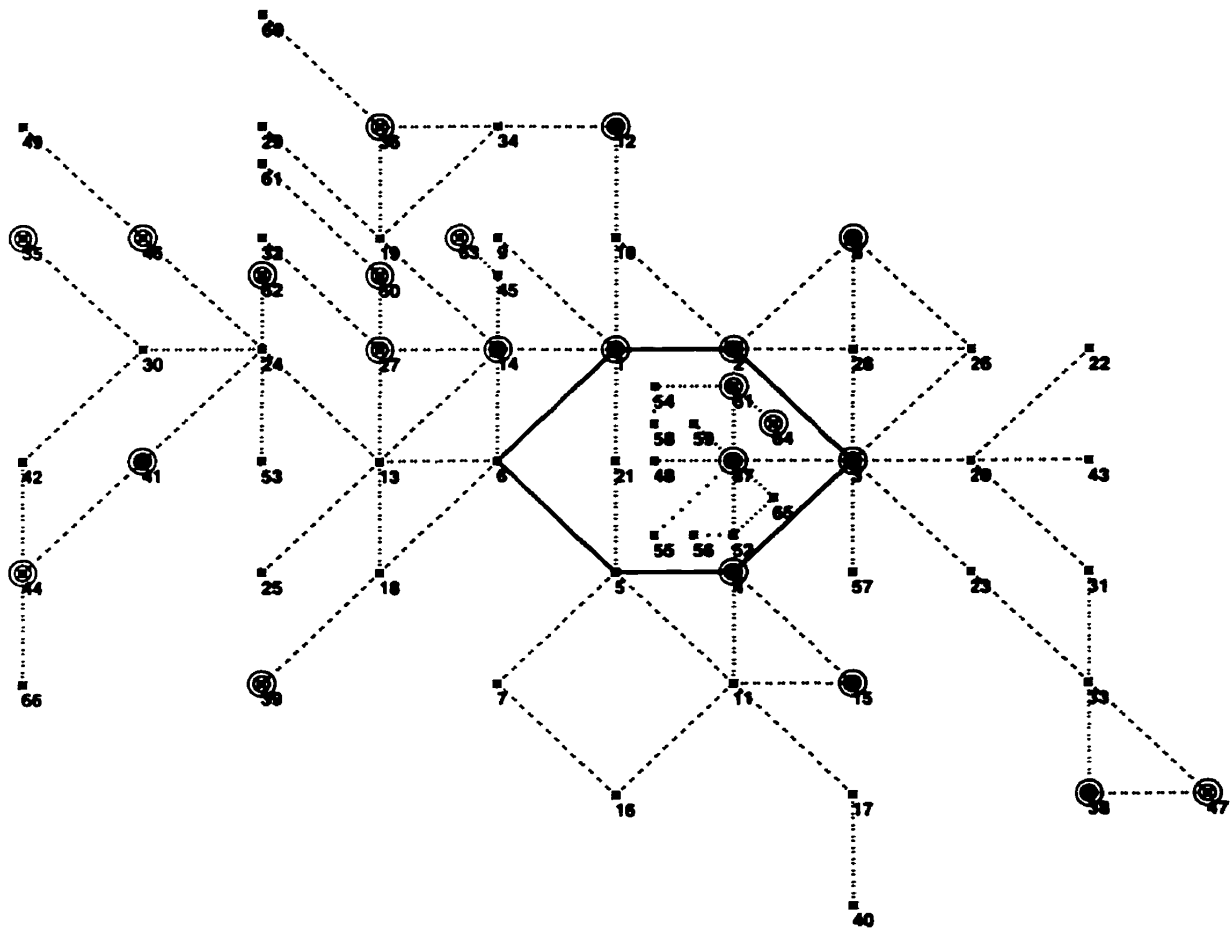


Figure A.2: A 66-bus network with 86 lines - network layout.

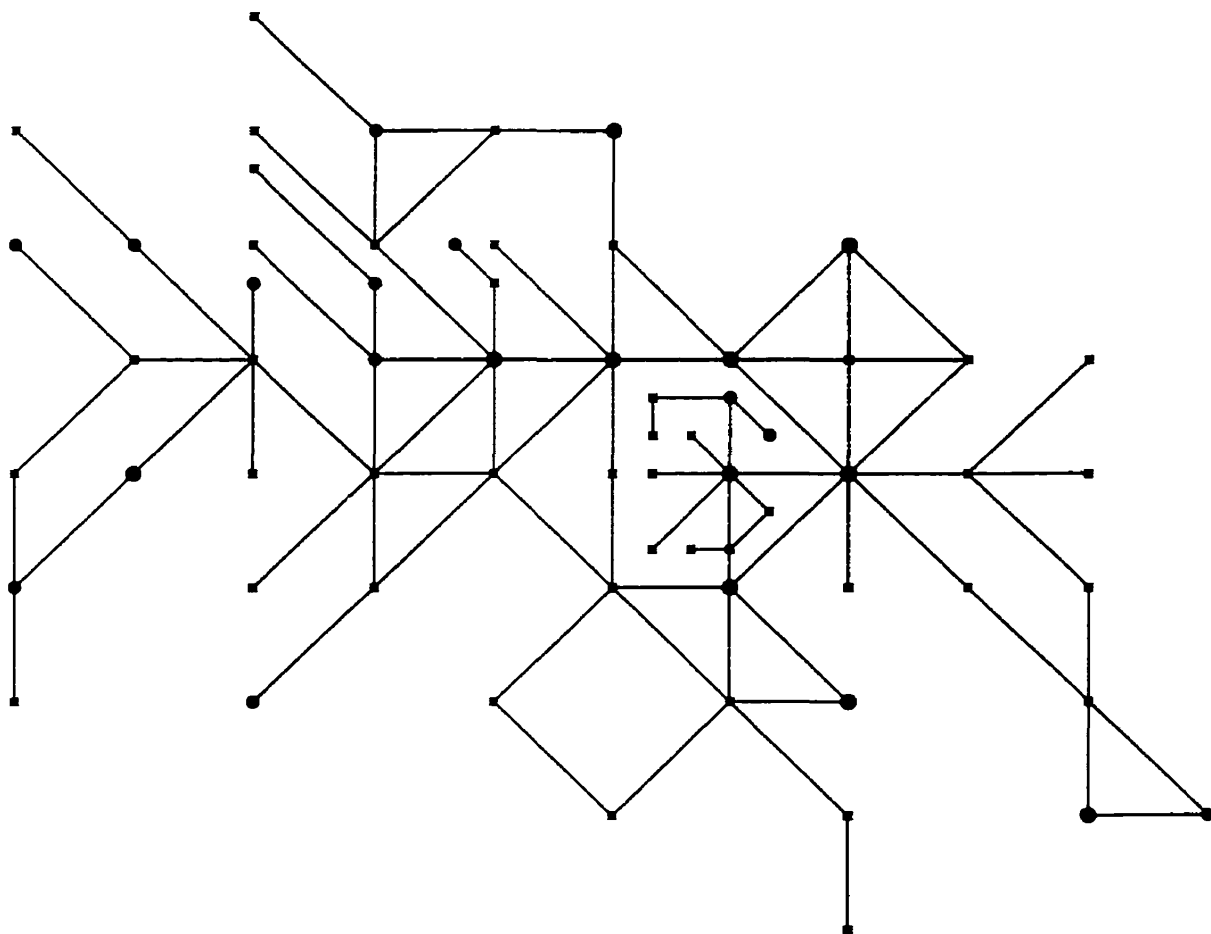


Figure A.3: A 66-bus network with 86 lines - topology layout.

Line Data

Table A.1: Line data for network of 66 buses and 86 lines.

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the Line (km)
				R (Ω)	X (Ω)	B (mS)			
1	1 - 2	735	3	0.2467	6.8907	0.8117	0.00	14.24	59
2	2 - 3	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
3	3 - 4	735	10	0.1600	4.4697	5.8501	0.00	47.48	128
4	4 - 5	735	10	0.2000	5.5871	7.3126	0.00	47.48	160
5	5 - 6	735	5	0.2600	7.2632	2.3766	0.00	23.74	104
6	6 - 1	735	9	0.1556	4.3455	4.6070	0.00	42.73	112
7	5 - 7	735	2	0.4812	13.4439	0.7038	0.00	9.50	77
8	2 - 8	735	2	1.0812	30.2052	1.5814	0.00	9.50	173
9	1 - 9	735	2	0.8750	24.4435	1.2797	0.00	9.50	140
10	1 - 10	735	2	0.4562	12.7455	0.6673	0.00	9.50	73
11	5 - 11	735	2	0.7000	19.5548	1.0238	0.00	9.50	112
12	10 - 12	735	2	0.2312	6.4601	0.3382	0.00	9.50	37
13	2 - 10	735	2	1.0562	29.5068	1.5448	0.00	9.50	169
14	4 - 11	735	2	1.6188	45.2204	2.3675	0.00	9.50	259
15	6 - 13	735	2	0.0375	1.0476	0.0548	0.00	9.50	6
16	1 - 14	735	2	0.3437	9.6028	0.5027	0.00	9.50	55
17	4 - 15	735	2	0.8062	22.5229	1.1792	0.00	9.50	129
18	14 - 6	735	2	0.5688	15.8883	0.8318	0.00	9.50	91
19	11 - 16	735	2	0.1875	5.2379	0.2742	0.00	9.50	30
20	11 - 17	500	2	0.2604	5.4113	0.2338	375.00	5.60	28

Table A.1: Line data for network of 66 buses and 86 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
21	6 - 18	500	2	0.8929	18.5530	0.8014	375.00	5.60	96
22	15 - 11	735	2	0.9188	25.6657	1.3437	0.00	9.50	147
23	14 - 19	735	2	1.0312	28.8084	1.5082	0.00	9.50	165
24	3 - 20	735	2	0.7812	21.8245	1.1426	0.00	9.50	125
25	1 - 21	735	2	0.1125	3.1427	0.1645	0.00	9.50	18
26	13 - 18	500	3	0.6263	13.0129	1.2648	125.00	8.40	101
27	20 - 22	735	2	0.0500	1.3968	0.0731	0.00	9.50	8
28	3 - 23	735	2	0.2125	5.9363	0.3108	0.00	9.50	34
29	13 - 24	735	3	0.4958	13.8513	1.6316	0.00	14.24	119
30	7 - 16	735	2	0.7062	19.7294	1.0329	0.00	9.50	113
31	13 - 25	735	2	1.6875	47.1410	2.4680	0.00	9.50	270
32	3 - 26	735	3	0.2083	5.8199	0.6856	0.00	14.24	50
33	14 - 27	500	2	0.5209	10.8226	0.4675	375.00	5.60	56
34	21 - 5	735	2	0.7000	19.5548	1.0238	0.00	9.50	112
35	3 - 28	735	3	1.0458	29.2158	3.4415	0.00	14.24	251
36	19 - 29	735	2	0.4375	12.2217	0.6399	0.00	9.50	70
37	24 - 30	735	2	1.0438	29.1576	1.5265	0.00	9.50	167
38	13 - 27	500	3	0.6015	12.4975	1.2147	93.75	8.40	97
39	20 - 31	500	2	0.0651	1.3528	0.0584	375.00	5.60	7
40	27 - 32	500	2	1.5626	32.4678	1.4025	0.00	5.60	168
41	23 - 33	735	2	0.3625	10.1266	0.5302	0.00	9.50	58
42	26 - 8	735	2	0.5062	14.1423	0.7404	0.00	9.50	81

Table A.1: Line data for network of 66 buses and 86 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
43	19 - 34	735	2	0.3938	10.9996	0.5759	0.00	9.50	63
44	30 - 35	500	2	0.2139	4.4450	0.1920	375.00	5.60	23
45	19 - 36	500	2	0.0465	0.9663	0.0417	375.00	5.60	5
46	34 - 36	500	2	0.5860	12.1754	0.5259	187.50	5.60	63
47	3 - 37	735	3	1.6708	46.6754	5.4982	0.00	14.24	401
48	33 - 38	735	2	0.2562	7.1584	0.3748	0.00	9.50	41
49	18 - 39	345	2	0.9948	10.4684	0.2980	179.00	2.90	44
50	26 - 28	735	2	0.7375	20.6024	1.0786	0.00	9.50	118
51	17 - 40	345	2	2.2790	23.9823	0.6828	179.00	2.90	101
52	24 - 41	735	2	0.9375	26.1894	1.3711	0.00	9.50	150
53	30 - 42	735	2	0.6125	17.1104	0.8958	0.00	9.50	98
54	14 - 13	735	2	0.5187	14.4915	0.7587	0.00	9.50	83
55	20 - 43	500	2	0.3851	8.0010	0.3456	375.00	5.60	41
56	42 - 44	500	2	0.6511	13.5283	0.5844	375.00	5.60	70
57	14 - 45	735	2	0.4875	13.6185	0.7130	0.00	9.50	78
58	12 - 34	735	2	1.3937	38.9350	2.0384	0.00	9.50	223
59	24 - 46	500	2	0.1116	2.3191	0.1002	375.00	5.60	12
60	33 - 47	735	2	1.8250	50.9821	2.6691	0.00	9.50	292
61	37 - 48	735	2	0.4000	11.1742	0.5850	0.00	9.50	64
62	38 - 47	735	2	0.6562	18.3326	0.9598	0.00	9.50	105
63	46 - 49	345	2	1.9896	20.9369	0.5961	179.00	2.90	88
64	27 - 50	345	2	0.7913	8.3272	0.2371	179.00	2.90	35

Table A.1: Line data for network of 66 buses and 86 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
65	37 - 51	500	2	0.2046	4.2517	0.1837	375.00	5.60	22
66	8 - 28	735	2	0.1375	3.8411	0.2011	0.00	9.50	22
67	37 - 52	735	2	0.4687	13.0947	0.6856	0.00	9.50	75
68	24 - 53	735	2	0.3312	9.2536	0.4845	0.00	9.50	53
69	51 - 54	500	2	0.7162	14.8811	0.6428	0.00	5.60	77
70	4 - 52	735	2	1.8750	52.3789	2.7422	0.00	9.50	300
71	37 - 55	500	2	0.4651	9.6630	0.4174	375.00	5.60	50
72	52 - 56	735	2	0.9500	26.5386	1.3894	0.00	9.50	152
73	3 - 57	735	6	0.1604	4.4813	2.1115	0.00	28.49	77
74	2 - 28	735	2	0.7000	19.5548	1.0238	0.00	9.50	112
75	54 - 58	345	2	0.4296	4.5205	0.1287	179.00	2.90	19
76	37 - 59	735	2	0.0625	1.7460	0.0914	0.00	9.50	10
77	36 - 60	345	2	1.3791	14.5131	0.4132	179.00	2.90	61
78	33 - 31	500	2	0.1116	2.3191	0.1002	93.75	5.60	12
79	50 - 61	345	3	2.4323	29.8236	3.1142	0.00	6.28	240
80	24 - 62	500	2	0.1209	2.5124	0.1085	375.00	5.60	13
81	45 - 63	500	2	0.2046	4.2517	0.1837	375.00	5.60	22
82	41 - 44	500	3	1.3766	28.6026	2.7800	125.00	8.40	222
83	51 - 64	345	2	0.5652	5.9480	0.1693	179.00	2.90	25
84	52 - 65	735	2	0.4812	13.4439	0.7038	0.00	9.50	77
85	44 - 66	500	2	1.8882	39.2320	1.6947	0.00	5.60	203
86	37 - 65	735	2	0.5938	16.5866	0.8684	0.00	9.50	95

Bus Data

Table A.2: Voltage regulated bus data for network of 66 buses and 86 lines.

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MW)	Q_{gmin} (MVar)	Q_{gmax} (MVar)	P_d (MW)	Q_d (MVar)
1	1.0000	23360.00	17109.62	0.00	1737.00	4900.00	295.82
2	0.9944	4280.00	4277.63	-30.00	50.00	2765.18	1390.91
3	1.0000	49710.00	49674.10	0.00	3832.00	10500.00	1479.08
4	1.0007	3620.00	3616.71	-30.00	50.00	1372.42	1872.89
5	0.9800	0.00	0.00	-2732.00	2732.00	2146.06	1516.39
8	0.9998	11290.00	11283.63	-30.00	50.00	3667.20	-5502.08
12	0.9874	2190.00	2183.98	-30.00	50.00	1691.85	550.15
14	0.9939	5220.00	5205.01	-30.00	50.00	703.55	360.52
15	1.0008	2950.00	2947.31	-30.00	50.00	1826.10	-178.68
27	1.0000	0.00	0.00	-44.00	72.00	172.23	122.96
35	1.0000	0.00	0.00	-50.00	115.00	199.78	65.67
36	1.0000	0.00	0.00	-30.00	50.00	151.75	79.77
37	1.0000	1660.00	1657.42	0.00	389.00	1497.38	1120.30
38	0.9523	4140.00	4137.61	-30.00	50.00	2711.97	1152.26
39	1.0000	0.00	0.00	-52.00	86.00	219.71	72.22
41	0.9686	1740.00	1739.01	-30.00	50.00	1642.75	410.07
44	1.0000	0.00	0.00	-60.00	100.00	452.47	393.50
46	1.0000	0.00	0.00	-35.00	57.00	21.63	69.02
50	1.0000	0.00	0.00	0.00	327.00	91.98	371.16
51	1.0000	0.00	0.00	0.00	468.00	63.28	220.64

Table A.2: Voltage regulated bus data for network of 66 buses and 86 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
62	1.0000	0.00	0.00	-30.00	50.00	63.67	20.93
63	1.0000	0.00	0.00	0.00	324.00	461.67	151.74
64	1.0000	0.00	0.00	-58.00	96.00	198.59	65.27

Table A.3: Load (PQ) Bus Data

Bus No	P_d (MW)	Q_d (MVA _r)
6	2969.49	1067.32
7	1896.56	1010.44
9	674.04	221.55
10	1901.12	912.01
11	2368.36	1555.24
13	3083.34	3387.04
16	3440.22	1233.57
17	21.43	74.45
18	408.09	40.82
19	74.33	656.10
20	9.03	123.92
21	1164.75	621.90
22	951.03	312.59
23	622.69	226.70
24	34.44	1686.40
25	1212.29	398.46
26	751.22	2750.27
28	19873.56	6342.39
29	945.99	310.93
30	221.04	566.43

Table A.13: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
31	149.76	12.27
32	323.34	106.28
33	197.54	1407.73
34	1741.91	942.92
40	63.79	20.97
42	663.60	344.33
43	79.61	26.17
45	77.50	13.89
47	4498.06	-33.37
48	1214.79	399.28
49	75.98	24.97
52	1983.35	1224.59
53	497.40	163.49
54	207.21	68.82
55	165.90	54.53
56	706.38	232.18
57	7939.16	2609.48
58	87.63	28.80
59	672.12	220.92
60	47.70	15.68

Table A.13: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
61	357.70	117.57
65	1019.02	265.97
66	525.32	172.66

Load-Flow Solution

Table A.4: Load-flow solution for 66-bus and 86-line network.

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
1**	17109.62	1736.55	4900.00	295.82	1.0000	0.0000
2	4277.63	0.00	2765.18	1390.91	0.9944	0.0161
3	49674.10	3831.61	10500.00	1479.08	1.0000	0.0791
4	3616.71	0.00	1372.42	1872.89	1.0007	0.0075
5	0.00	-2731.17	2146.06	1516.39	0.9800	-0.0543
6	0.00	0.00	2969.49	1067.32	0.9856	-0.0616
7	0.00	0.00	1896.56	1010.44	0.9577	-0.1225
8	11283.63	0.00	3667.20	-5502.08	0.9998	-0.0321
9	0.00	0.00	674.04	221.55	1.0042	-0.0306
10	0.00	0.00	1901.12	912.01	0.9895	-0.0382
11	0.00	0.00	2368.36	1555.24	0.9632	-0.1216
12	2183.98	0.00	1691.85	550.15	0.9874	-0.0466

**Bus number 1 is selected as a slack and a reference bus for this presented load-flow solution

Table A.4: Load-flow solution for 66-bus and 86-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
13	0.00	0.00	3083.34	3387.04	0.9810	-0.0740
14	5205.01	0.00	703.55	360.52	0.9939	-0.0224
15	2947.31	0.00	1826.10	-178.68	1.0008	-0.0270
16	0.00	0.00	3440.22	1233.57	0.9533	-0.1503
17	0.00	0.00	21.43	74.45	0.9508	-0.2639
18	0.00	0.00	408.09	40.82	1.0266	-0.3286
19	0.00	0.00	74.33	656.10	0.9748	-0.1203
20	0.00	0.00	9.03	123.92	0.9951	0.0343
21	0.00	0.00	1164.75	621.90	0.9953	-0.0132
22	0.00	0.00	951.03	312.59	0.9942	0.0319
23	0.00	0.00	622.69	226.70	0.9836	0.0348
24	0.00	0.00	34.44	1686.40	0.9635	-0.1461
25	0.00	0.00	1212.29	398.46	0.9942	-0.1836
26	0.00	0.00	751.22	2750.27	0.9774	0.0175
27	0.00	65.27	172.23	122.96	1.0000	-0.3909
28	0.00	0.00	19873.56	6342.39	0.9638	-0.1067
29	0.00	0.00	945.99	310.93	0.9703	-0.1428
30	0.00	0.00	221.04	566.43	0.9544	-0.2241
31	0.00	0.00	149.76	12.27	0.9676	-0.0669
32	0.00	0.00	323.34	106.28	1.0063	-0.4331
33	0.00	0.00	197.54	1407.73	0.9600	-0.0316
34	0.00	0.00	1741.91	942.92	0.9725	-0.1350
35	0.00	104.44	199.78	65.67	1.0000	-0.5475

Table A.4: Load-flow solution for 66-bus and 86-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
36	0.00	40.80	151.75	79.77	1.0000	-0.2371
37	1657.42	388.02	1497.38	1120.30	1.0000	-0.2367
38	4137.61	0.01	2711.97	1152.26	0.9523	-0.0562
39	0.00	77.56	219.71	72.22	1.0000	-0.6765
40	0.00	0.00	63.79	20.97	0.9737	-0.3820
41	1739.01	0.01	1642.75	410.07	0.9686	-0.1797
42	0.00	0.00	663.60	344.33	0.9501	-0.2557
43	0.00	0.00	79.61	26.17	1.0154	-0.0867
44	0.00	90.64	452.47	393.50	1.0000	-0.6668
45	0.00	0.00	77.50	13.89	0.9936	-0.0362
46	0.00	51.34	21.63	69.02	1.0000	-0.2998
47	0.00	0.00	4498.06	-33.37	0.9674	-0.1725
48	0.00	0.00	1214.79	399.28	0.9937	-0.2618
49	0.00	0.00	75.98	24.97	1.0093	-0.4267
50	0.00	326.51	91.98	371.16	1.0000	-1.1850
51	0.00	467.69	63.28	220.64	1.0000	-1.2442
52	0.00	0.00	1983.35	1224.59	1.0004	-0.2479
53	0.00	0.00	497.40	163.49	0.9624	-0.1552
54	0.00	0.00	207.21	68.82	0.9980	-1.2617
55	0.00	0.00	165.90	54.53	0.9511	-0.5084
56	0.00	0.00	706.38	232.18	1.0057	-0.2826
57	0.00	0.00	7939.16	2609.48	0.9779	0.0123
58	0.00	0.00	87.63	28.80	0.9521	-1.4043

Table A.4: Load-flow solution for 66-bus and 86-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
59	0.00	0.00	672.12	220.92	0.9993	-0.2388
60	0.00	0.00	47.70	15.68	1.0118	-0.3139
61	0.00	0.00	357.70	117.57	1.0061	-1.2756
62	0.00	34.76	63.67	20.93	1.0000	-0.2461
63	0.00	323.69	461.67	151.74	1.0000	-0.8186
64	0.00	87.24	198.59	65.27	1.0000	-1.5581
65	0.00	0.00	1019.02	265.97	1.0018	-0.2569
66	0.00	0.00	525.32	172.66	0.9987	-0.7498

Table A.5: Load-flow solution for 66-bus and 86-line network - line flows.

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVAR)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
1	1 - 2	-1240.76	274.26	19.55	-0.2116	-0.0358	0.0789
2	2 - 3	-4841.58	-495.70	19.55	-0.6191	-0.1415	0.2017
3	3 - 4	8647.45	-1663.50	19.55	0.4423	0.1617	0.1452
4	4 - 5	5925.30	-7.13	19.55	0.3031	0.1385	0.1177
5	5 - 6	510.88	-1040.93	19.55	0.0523	0.0155	0.0184
6	6 - 1	-7589.34	-2469.31	19.55	-0.4313	-0.1380	0.1416
7	5 - 7	2601.76	691.09	19.55	0.6654	0.1463	0.2370
8	2 - 8	853.63	-527.40	19.55	0.2183	0.1079	0.0758
9	1 - 9	674.80	-451.56	19.55	0.1726	0.0690	0.0592
10	1 - 10	1616.27	239.56	19.55	0.4134	0.0862	0.1426
11	5 - 11	1771.28	184.45	19.55	0.4530	0.1449	0.1613
12	10 - 12	692.07	54.99	19.55	0.1770	0.0187	0.0611
13	2 - 10	981.19	-331.05	19.55	0.2509	0.1211	0.0914
14	4 - 11	1500.45	-150.24	19.55	0.3837	0.2789	0.1553
15	6 - 13	6272.80	2119.72	19.55	1.6043	0.0275	0.5565
16	1 - 14	1265.52	175.85	19.55	0.3237	0.0508	0.1110
17	4 - 15	827.12	-337.97	19.55	0.2115	0.0779	0.0727
18	14 - 6	1313.77	37.31	19.55	0.3360	0.0873	0.1164
19	11 - 16	2745.85	853.11	19.55	0.7023	0.0602	0.2507
20	11 - 17	85.31	-13.23	8.22	0.0519	0.0043	0.0203
21	6 - 18	169.57	-100.58	8.22	0.1031	0.0292	0.0406
22	15 - 11	1947.31	450.20	19.55	0.4980	0.2091	0.1881
23	14 - 19	1789.22	-22.99	19.55	0.4576	0.2157	0.1625
24	3 - 20	1106.16	-201.34	19.55	0.2829	0.1010	0.0978

Table A.5: Load-flow solution for 66-bus and 86-line - network line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
25	1 - 21	2286.92	696.43	19.55	0.5849	0.0301	0.2000
26	13 - 18	459.30	-176.38	8.22	0.1863	0.0555	0.0668
27	20 - 22	951.12	276.10	19.55	0.2433	0.0056	0.0833
28	3 - 23	4015.96	1352.34	19.55	1.0271	0.0997	0.3552
29	13 - 24	2677.81	247.52	19.55	0.4566	0.1552	0.1626
30	7 - 16	698.21	-157.58	19.55	0.1786	0.0576	0.0676
31	13 - 25	1217.15	-766.35	19.55	0.3113	0.2355	0.1115
32	3 - 26	5659.18	1884.58	19.55	0.9649	0.1378	0.3359
33	14 - 27	232.01	-18.74	8.22	0.1411	0.0233	0.0521
34	21 - 5	1120.97	129.37	19.55	0.2867	0.0917	0.1088
35	3 - 28	3322.62	-71.57	19.55	0.5665	0.3994	0.2081
36	19 - 29	946.78	6.03	19.55	0.2421	0.0484	0.0852
37	24 - 30	1333.62	-216.19	19.55	0.3411	0.1627	0.1238
38	13 - 27	719.63	-79.07	8.22	0.2918	0.0834	0.1052
39	20 - 31	64.60	14.21	8.22	0.0393	0.0008	0.0146
40	27 - 32	324.02	-232.51	8.22	0.1971	0.0976	0.0711
41	23 - 33	3386.11	1090.91	19.55	0.8660	0.1435	0.3071
42	26 - 8	1819.03	-1045.77	19.55	0.4652	0.1076	0.1639
43	19 - 34	686.14	-59.26	19.55	0.1755	0.0316	0.0616
44	30 - 35	199.82	-18.07	8.22	0.1215	0.0082	0.0435
45	19 - 36	75.51	-16.90	8.22	0.0459	0.0007	0.0160
46	34 - 36	124.01	-89.67	8.22	0.0754	0.0140	0.0273
47	3 - 37	3610.13	-1042.13	19.55	0.6155	0.6759	0.2257

Table A.5: Load-flow solution for 66-bus and 86-line - network line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
48	33 - 38	1713.62	423.67	19.55	0.4383	0.0513	0.1567
49	18 - 39	220.12	35.92	3.18	0.3461	0.0499	0.1304
50	26 - 28	3074.93	150.98	19.55	0.7864	0.2651	0.2670
51	17 - 40	63.88	-46.41	3.18	0.1004	0.0332	0.0421
52	24 - 41	643.55	-457.69	19.55	0.1646	0.0705	0.0587
53	30 - 42	909.00	-111.25	19.55	0.2325	0.0651	0.0838
54	14 - 13	1891.23	255.17	19.55	0.4837	0.1147	0.1667
55	20 - 43	79.62	-51.24	8.22	0.0484	0.0059	0.0180
56	42 - 44	244.35	-45.90	8.22	0.1486	0.0307	0.0562
57	14 - 45	539.65	-195.67	19.55	0.1380	0.0307	0.0475
58	12 - 34	1183.98	-322.75	19.55	0.3028	0.1903	0.1175
59	24 - 46	97.71	-27.45	8.22	0.0594	0.0021	0.0209
60	33 - 47	1380.79	-692.33	19.55	0.3531	0.2880	0.1310
61	37 - 48	1215.94	117.37	19.55	0.3110	0.0568	0.1068
62	38 - 47	3137.62	-589.56	19.55	0.8025	0.2407	0.2727
63	46 - 49	76.08	-36.91	3.18	0.1196	0.0345	0.0481
64	27 - 50	453.97	174.00	3.18	0.7138	0.0819	0.2868
65	37 - 51	557.52	283.95	8.22	0.3391	0.0220	0.1335
66	8 - 28	10283.63	5016.63	19.55	2.6301	0.1653	0.9507
67	37 - 52	460.25	-214.12	19.55	0.1177	0.0252	0.0402
68	24 - 53	497.56	-74.57	19.55	0.1273	0.0193	0.0451
69	51 - 54	295.12	-58.25	8.22	0.1795	0.0407	0.0644
70	4 - 52	2616.71	-497.23	19.55	0.6692	0.5600	0.2312

Table A.5: Load-flow solution for 66-bus and 86-line - network line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
71	37 - 55	165.95	2.04	8.22	0.1009	0.0149	0.0406
72	52 - 56	707.29	-497.71	19.55	0.1809	0.0785	0.0621
73	3 - 57	7960.06	2077.53	19.55	0.6786	0.1492	0.2367
74	2 - 28	3277.63	650.80	19.55	0.8383	0.2682	0.2903
75	54 - 58	87.66	28.10	3.18	0.1378	0.0086	0.0565
76	37 - 59	672.18	173.16	19.55	0.1719	0.0049	0.0586
77	36 - 60	47.73	-30.32	3.18	0.0750	0.0150	0.0296
78	33 - 31	85.16	-29.08	8.22	0.0518	0.0018	0.0183
79	50 - 61	360.38	-222.47	4.05	0.2966	0.2222	0.1038
80	24 - 62	63.67	-32.73	8.22	0.0387	0.0015	0.0137
81	45 - 63	461.88	163.39	8.22	0.2809	0.0182	0.1052
82	41 - 44	739.01	-198.81	8.22	0.2997	0.1936	0.1230
83	51 - 64	198.78	20.75	3.18	0.3126	0.0256	0.1171
84	52 - 65	362.20	-258.66	19.55	0.0926	0.0204	0.0316
85	44 - 66	527.42	-206.79	8.22	0.3208	0.1899	0.1176
86	37 - 65	657.42	-309.55	19.55	0.1681	0.0456	0.0560

A.2 A 66-bus Network with 124 lines

This network was developed from a 6-bus core ring network, by adding sixty new buses. The mesh density requirements were relatively high - a new loop connection was attempted after each new bus was placed. Although the new generation was not limited, the obtained network was not developed in full - out of the 126 required lines, 124 were successfully added.

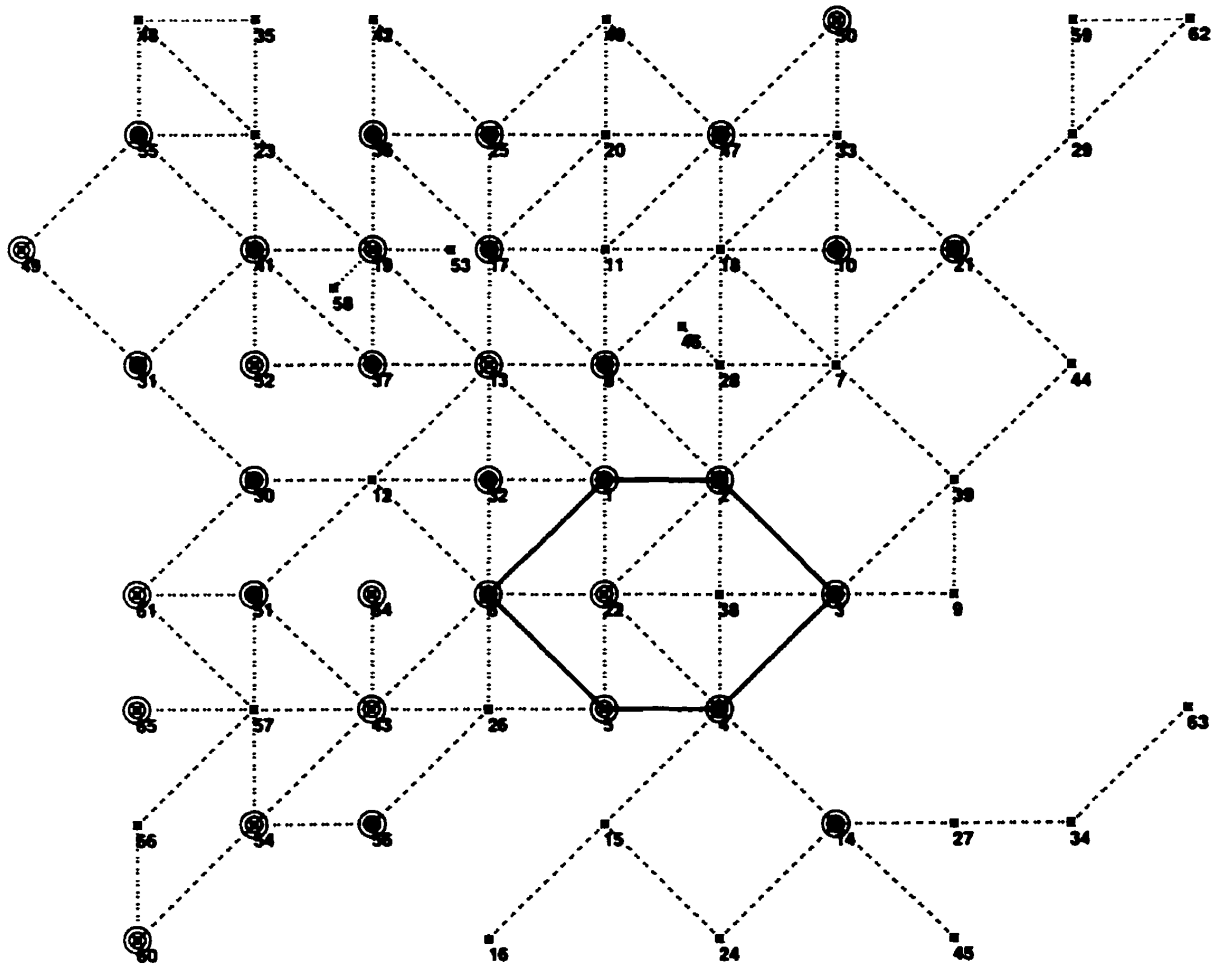


Figure A.4: A 66-bus network with 124 lines - network layout.

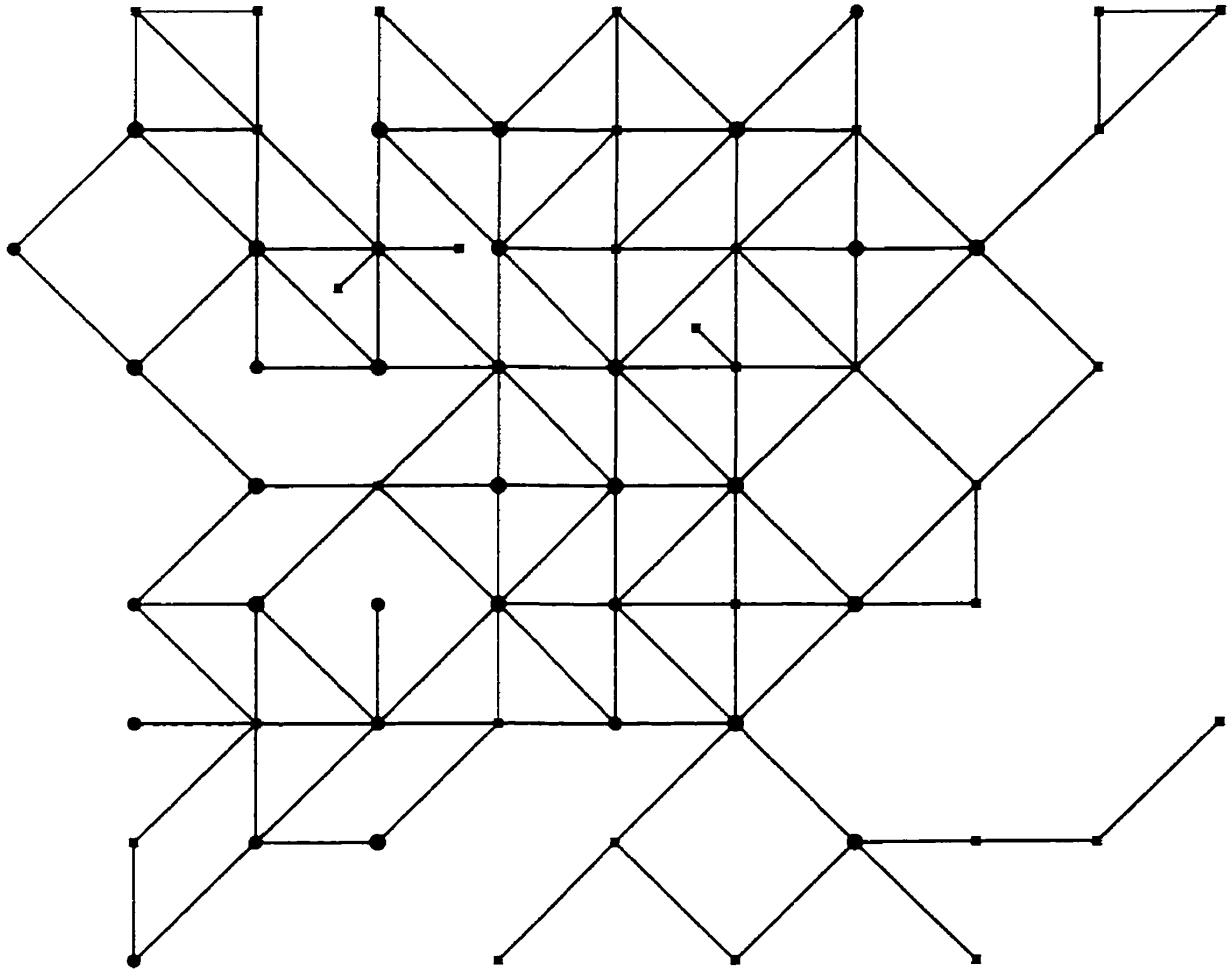


Figure A.5: A 66-bus network with 124 lines - topology layout.

Line Data

Table A.6: Line data for network of 66 buses and 124 lines.

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the Line (km)
				R ($m\Omega$)	X ($m\Omega$)	B (μS)			
1	1 - 2	735	3	0.2467	6.8907	0.8117	0.00	14.24	59
2	2 - 3	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
3	3 - 4	735	10	0.1600	4.4697	5.8501	0.00	47.48	128
4	4 - 5	735	10	0.2000	5.5871	7.3126	0.00	47.48	160
5	5 - 6	735	5	0.2600	7.2632	2.3766	0.00	23.74	104
6	6 - 1	735	9	0.1556	4.3455	4.6070	0.00	42.73	112
7	2 - 7	735	4	0.5062	14.1423	2.9616	0.00	18.99	162
8	2 - 8	500	2	0.0372	0.7730	0.0334	375.00	5.60	4
9	1 - 8	500	2	1.1999	24.9307	1.0769	187.50	5.60	129
10	3 - 9	735	2	0.3625	10.1266	0.5302	0.00	9.50	58
11	7 - 10	735	2	0.4625	12.9201	0.6764	0.00	9.50	74
12	8 - 11	345	2	3.1652	33.3087	0.9483	179.00	2.90	140
13	6 - 12	735	3	0.2250	6.2855	0.7404	0.00	14.24	54
14	1 - 13	500	2	0.3348	6.9574	0.3005	375.00	5.60	36
15	12 - 13	500	5	0.2939	6.1070	1.6488	53.57	14.00	79
16	8 - 13	500	3	1.2030	24.9951	2.4294	0.00	8.40	194
17	4 - 14	735	2	0.9687	27.0624	1.4168	0.00	9.50	155
18	4 - 15	735	2	1.6562	46.2680	2.4223	0.00	9.50	265
19	15 - 16	735	2	0.5000	13.9677	0.7313	0.00	9.50	80
20	8 - 17	500	2	0.2046	4.2517	0.1837	0.00	5.60	22

Table A.6: Line data for network of 66 buses and 124 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
21	17 - 11	345	5	0.1642	2.0131	0.5839	22.38	10.47	27
22	8 - 18	500	2	1.2929	26.8633	1.1604	0.00	5.60	139
23	10 - 18	500	2	0.6232	12.9485	0.5593	125.00	5.60	67
24	18 - 11	345	3	1.0641	13.0478	1.3625	89.50	6.28	105
25	13 - 19	500	2	4.8224	56.8778	3.3861	0.00	5.77	347
26	11 - 20	345	2	1.3530	16.5894	0.7699	0.00	4.19	89
27	17 - 20	345	2	3.2228	39.5163	1.8339	89.50	4.19	212
28	7 - 18	500	2	0.6883	14.3013	0.6178	125.00	5.60	74
29	7 - 21	735	2	0.9062	25.3165	1.3254	0.00	9.50	145
30	1 - 22	500	2	0.8185	17.0070	0.7347	375.00	5.60	88
31	5 - 22	500	2	0.4744	9.8563	0.4258	75.00	5.60	51
32	2 - 22	500	2	1.3673	28.4093	1.2272	187.50	5.60	147
33	19 - 23	500	2	2.8462	59.1378	2.5546	0.00	5.60	306
34	6 - 22	500	2	0.8092	16.8137	0.7263	125.00	5.60	87
35	4 - 22	500	2	1.9626	40.7780	1.7615	187.50	5.60	211
36	17 - 13	500	3	1.5006	31.1794	3.0305	0.00	8.40	242
37	15 - 24	735	2	0.2312	6.4601	0.3382	0.00	9.50	37
38	10 - 21	735	2	0.1750	4.8887	0.2559	0.00	9.50	28
39	14 - 24	735	2	1.2188	34.0463	1.7825	0.00	9.50	195
40	17 - 25	500	2	2.8629	33.7661	2.0102	0.00	5.77	206
41	25 - 20	345	2	1.2314	15.0982	0.7007	89.50	4.19	81
42	5 - 26	735	5	0.4300	12.0122	3.9305	0.00	23.74	172

Table A.6: Line data for network of 66 buses and 124 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
43	6 - 26	735	2	1.4062	39.2842	2.0567	0.00	9.50	225
44	14 - 27	735	2	1.4062	39.2842	2.0567	0.00	9.50	225
45	8 - 28	345	2	0.4070	4.2825	0.1219	179.00	2.90	18
46	7 - 28	345	2	2.4627	30.1964	1.4014	89.50	4.19	162
47	18 - 28	345	4	0.0456	0.5592	0.1038	25.57	8.38	6
48	21 - 29	735	2	1.9000	53.0773	2.7788	0.00	9.50	304
49	12 - 30	735	2	0.5312	14.8407	0.7770	0.00	9.50	85
50	2 - 28	345	3	1.1655	14.2905	1.4922	59.67	6.28	115
51	30 - 31	500	2	0.4372	9.0833	0.3924	375.00	5.60	47
52	1 - 32	500	2	0.4744	9.8563	0.4258	375.00	5.60	51
53	6 - 32	500	2	0.8929	18.5530	0.8014	187.50	5.60	96
54	10 - 33	735	2	0.9400	26.2593	1.3748	0.00	9.50	150
55	33 - 18	500	3	0.1550	3.2210	0.3131	62.50	8.40	25
56	27 - 34	735	2	0.3375	9.4282	0.4936	0.00	9.50	54
57	23 - 35	500	2	0.9952	20.6789	0.8933	0.00	5.60	107
58	17 - 36	500	3	1.9099	39.6829	3.8569	0.00	8.40	308
59	21 - 33	735	2	0.1937	5.4125	0.2834	0.00	9.50	31
60	36 - 19	500	3	1.4820	30.7929	2.9929	0.00	8.40	239
61	25 - 36	500	2	1.5533	32.2746	1.3942	0.00	5.60	167
62	13 - 37	500	4	0.6743	14.0114	2.4210	0.00	11.20	145
63	32 - 13	500	2	2.8090	58.3648	2.5212	0.00	5.60	302
64	37 - 19	500	2	1.6091	33.4341	1.4443	0.00	5.60	173

Table A.6: Line data for network of 66 buses and 124 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
65	22 - 38	500	2	1.8789	39.0387	1.6864	0.00	5.60	202
66	2 - 38	500	5	0.2195	4.5610	1.2314	53.57	14.00	59
67	3 - 38	500	6	0.2263	4.7027	1.8283	53.57	16.80	73
68	4 - 38	500	8	0.0651	1.3528	0.9350	25.00	22.40	28
69	7 - 39	735	2	0.2250	6.2855	0.3291	0.00	9.50	36
70	9 - 39	735	2	0.5000	13.9677	0.7313	0.00	9.50	80
71	3 - 39	735	2	2.1125	59.0135	3.0896	0.00	9.50	338
72	20 - 40	345	2	3.2988	40.4483	1.8772	0.00	4.19	217
73	25 - 40	345	2	3.0404	37.2795	1.7301	89.50	4.19	200
74	37 - 41	500	2	1.8323	38.0724	1.6446	0.00	5.60	197
75	31 - 41	500	2	1.3859	28.7959	1.2439	0.00	5.60	149
76	41 - 19	500	2	1.6184	33.6274	1.4526	0.00	5.60	174
77	36 - 42	500	2	1.5905	33.0476	1.4276	0.00	5.60	171
78	25 - 42	500	2	0.6046	12.5620	0.5426	0.00	5.60	65
79	26 - 43	735	2	0.6562	18.3326	0.9598	0.00	9.50	105
80	41 - 23	500	3	0.5147	10.6938	1.0394	0.00	8.40	83
81	39 - 44	735	2	1.2062	33.6971	1.7642	0.00	9.50	193
82	21 - 44	735	2	0.5938	16.5866	0.8684	0.00	9.50	95
83	14 - 45	500	2	0.0465	0.9663	0.0417	375.00	5.60	5
84	6 - 43	735	2	1.3125	36.6652	1.9196	0.00	9.50	210
85	28 - 46	345	2	0.7461	7.8513	0.2235	0.00	2.90	33
86	11 - 47	345	2	1.9896	20.9369	0.5961	0.00	2.90	88

Table A.6: Line data for network of 66 buses and 124 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
87	18 - 47	345	2	2.7515	33.7380	1.5658	89.50	4.19	181
88	47 - 20	345	2	1.1078	11.6580	0.3319	0.00	2.90	49
89	35 - 48	500	2	1.2185	25.3172	1.0936	0.00	5.60	131
90	23 - 48	500	2	1.1720	24.3509	1.0519	0.00	5.60	126
91	31 - 49	345	2	0.2261	2.3792	0.0677	179.00	2.90	10
92	33 - 47	345	4	0.5093	6.2443	1.1592	35.80	8.38	67
93	47 - 50	345	4	0.6993	8.5743	1.5917	0.00	8.38	92
94	12 - 32	500	3	0.1116	2.3191	0.2254	75.00	8.40	18
95	12 - 51	735	2	0.6562	18.3326	0.9598	0.00	9.50	105
96	51 - 43	735	2	0.2688	7.5076	0.3931	0.00	9.50	43
97	37 - 52	345	2	0.5878	6.1859	0.1761	179.00	2.90	26
98	41 - 52	345	3	1.7736	21.7464	2.2708	89.50	6.28	175
99	19 - 53	500	9	0.5663	11.7674	10.2935	0.00	25.20	274
100	47 - 40	345	2	2.5322	26.6470	0.7586	0.00	2.90	112
101	43 - 54	500	2	0.7534	15.6541	0.6762	375.00	5.60	81
102	33 - 50	345	4	1.0717	13.1410	2.4395	59.67	8.38	141
103	41 - 55	500	3	0.7069	14.6878	1.4276	0.00	8.40	114
104	55 - 49	345	3	2.4424	29.9479	3.1272	89.50	6.28	241
105	26 - 56	735	2	0.6812	19.0310	0.9963	0.00	9.50	109
106	55 - 48	500	3	1.3022	27.0565	2.6297	0.00	8.40	210
107	43 - 57	735	3	0.3917	10.9414	1.2889	0.00	14.24	94
108	55 - 23	500	3	0.9797	20.3568	1.9786	0.00	8.40	158

Table A.6: Line data for network of 66 buses and 124 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (A)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
109	19 - 58	500	3	1.6432	34.1428	3.3185	0.00	8.40	265
110	57 - 54	500	2	0.6139	12.7552	0.5510	125.00	5.60	66
111	29 - 59	735	2	0.6187	17.2850	0.9049	0.00	9.50	99
112	51 - 57	735	2	1.1000	30.7289	1.6088	0.00	9.50	176
113	54 - 60	345	2	0.9496	9.9926	0.2845	179.00	2.90	42
114	56 - 54	500	7	0.0478	0.9939	0.5259	25.00	19.60	18
115	57 - 61	500	2	1.0138	21.0654	0.9100	375.00	5.60	109
116	30 - 61	500	4	0.2883	5.9911	1.0352	46.88	11.20	62
117	29 - 62	735	2	0.0875	2.4443	0.1280	0.00	9.50	14
118	51 - 61	500	4	0.3720	7.7304	1.3357	62.50	11.20	80
119	34 - 63	735	2	0.2937	8.2060	0.4296	0.00	9.50	47
120	62 - 59	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
121	43 - 64	500	2	0.0465	0.9663	0.0417	375.00	5.60	5
122	57 - 65	735	2	2.3500	65.6482	3.4369	0.00	9.50	376
123	57 - 66	735	2	0.5375	15.0153	0.7861	0.00	9.50	86
124	66 - 60	345	3	2.0370	24.9773	2.6082	89.50	6.28	201

Bus Data

Table A.7: Voltage regulated bus data for network of 66 buses and 124 lines.

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MW)	Q_{gmin} (MVar)	Q_{gmax} (MVar)	P_d (MW)	Q_d (MVar)
1	1.0000	13500.00	7266.12	0.00	1077.00	12.32	440.40
2	0.9944	3970.00	3955.74	-15.00	40.00	2126.77	1462.89
3	1.0000	20750.00	20745.47	-168.00	168.00	319.83	592.99
4	1.0007	4250.00	4241.31	-30.00	50.00	1397.10	1735.79
5	0.9800	0.00	0.00	-2732.00	2732.00	598.59	1998.94
6	0.9856	3300.00	3296.87	-15.00	40.00	1617.08	1688.43
8	1.0000	5020.00	5017.48	-41.00	68.00	59.52	-220.72
10	0.9800	2420.00	2416.10	-30.00	50.00	769.18	1681.01
13	1.0000	0.00	0.00	-50.00	225.00	8237.45	-1210.90
14	1.0051	2200.00	2192.05	-30.00	50.00	126.36	1241.30
17	0.9954	6360.00	6351.06	-15.00	40.00	244.40	488.27
19	1.0000	0.00	0.00	-50.00	279.00	439.58	-81.72
21	0.9872	5570.00	5554.01	-30.00	50.00	2401.08	45.83
22	1.0000	0.00	0.00	-50.00	50.00	831.12	435.51
25	0.9783	6790.00	6779.02	-30.00	50.00	2316.60	763.37
30	0.9612	2860.00	2854.19	-30.00	50.00	1111.91	42.52
31	1.0000	2330.00	2328.98	-50.00	155.00	878.36	-115.10
32	0.9964	2720.00	2717.13	-30.00	50.00	1500.90	75.31
36	1.0000	4540.00	4537.46	-50.00	291.00	2842.12	258.14
37	0.9832	2490.00	2489.19	-30.00	50.00	1582.25	805.53

Table A.7: Voltage regulated bus data for network of 66 buses and 124 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
41	0.9784	7640.00	7633.40	-15.00	40.00	218.20	286.75
43	1.0000	0.00	0.00	0.00	1593.00	1045.60	-495.29
47	0.9562	1400.00	1399.94	-30.00	50.00	1174.66	778.94
49	1.0000	0.00	0.00	-50.00	300.00	800.06	178.69
50	1.0000	0.00	0.00	0.00	1013.00	1833.84	287.22
51	1.0000	2780.00	2776.58	0.00	1661.00	16.09	637.62
52	1.0000	0.00	0.00	-50.00	179.00	670.99	124.31
54	1.0000	0.00	0.00	-50.00	50.00	2275.91	-584.82
55	0.9521	6690.00	6677.37	-30.00	50.00	3001.18	1627.62
56	0.9544	3110.00	3107.68	-15.00	40.00	2160.47	618.83
60	1.0000	0.00	0.00	-51.00	84.00	556.31	96.21
61	1.0000	0.00	0.00	-50.00	50.00	3277.63	-480.87
64	1.0000	0.00	0.00	0.00	454.00	542.26	178.23
65	1.0000	0.00	0.00	0.00	754.00	2703.55	888.61

Table A.8: Load (PQ) Bus Data

Bus No	P_d (MW)	Q_d (MVar)
7	512.53	1658.10
9	884.53	1692.52
11	1230.40	135.84
12	1461.78	3568.00
15	157.49	632.47
16	593.18	194.97
18	676.28	35.01
20	673.62	395.69
23	8720.22	-1644.61
24	1694.34	463.33
26	2486.32	3513.33
27	832.75	527.52
28	515.06	76.90
29	160.22	579.41
33	447.40	267.49
34	283.10	318.61
35	38.53	273.31
38	7165.16	-289.79
39	3801.66	1209.42
40	864.57	155.92

Table A.13: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVar)
42	4337.71	-616.93
44	2663.27	690.91
45	52.94	17.40
46	389.42	128.00
48	3136.70	-297.89
53	4391.99	1443.58
57	620.77	2542.14
58	1353.37	444.83
59	1298.54	275.39
62	186.93	542.44
63	472.92	155.44
66	1587.85	763.91

Load-Flow Solution

Table A.9: Load-flow solution for the 66-bus and 124-line network.

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
1**	7266.12	1076.28	12.32	440.40	1.0000	0.0000
2	3955.74	-0.02	2126.77	1462.89	0.9944	0.0161
3	20745.47	-167.82	319.83	592.99	1.0000	0.0791
4	4241.31	0.06	1397.10	1735.79	1.0007	0.0075
5	0.00	-2731.17	598.59	1998.94	0.9800	-0.0543
6	3296.87	0.00	1617.08	1688.43	0.9856	-0.0616
7	0.00	0.00	512.53	1658.10	0.9822	-0.0650
8	5017.48	61.76	59.52	-220.72	1.0000	-0.2005
9	0.00	0.00	884.53	1692.52	0.9733	0.0065
10	2416.10	0.00	769.18	1681.01	0.9800	-0.0828
11	0.00	0.00	1230.40	135.84	0.9621	-0.4820
12	0.00	0.00	1461.78	3568.00	0.9599	-0.1320
13	0.00	204.29	8237.45	-1210.90	1.0000	-0.6105
14	2192.05	0.00	126.36	1241.30	1.0051	-0.0314
15	0.00	0.00	157.49	632.47	1.0130	-0.0997
16	0.00	0.00	593.18	194.97	1.0125	-0.1146
17	6351.06	0.00	244.40	488.27	0.9954	-0.2133
18	0.00	0.00	676.28	35.01	1.0006	-0.2385
19	0.00	253.18	439.58	-81.72	1.0000	-0.8948
20	0.00	0.00	673.62	395.69	0.9504	-0.5242

**Bus number 1 is selected as a slack and a reference bus for this presented load-flow solution

Table A.9: Load-flow solution for the 66-bus and 124-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
21	5554.01	0.00	2401.08	45.83	0.9872	-0.0963
22	0.00	-24.67	831.12	435.51	1.0000	-0.2366
23	0.00	0.00	8720.22	-1644.61	0.9931	-1.0722
24	0.00	0.00	1694.34	463.33	1.0119	-0.1055
25	6779.02	0.01	2316.60	763.37	0.9783	-0.3214
26	0.00	0.00	2486.32	3513.33	0.9619	-0.1546
27	0.00	0.00	832.75	527.52	0.9964	-0.1471
28	0.00	0.00	515.06	76.90	0.9811	-0.2811
29	0.00	0.00	160.22	579.41	0.9863	-0.2640
30	2854.19	0.00	1111.91	42.52	0.9612	-0.1439
31	2328.98	140.71	878.36	-115.10	1.0000	-0.6208
32	2717.13	0.00	1500.90	75.31	0.9964	-0.1996
33	0.00	0.00	447.40	267.49	0.9851	-0.1169
34	0.00	0.00	283.10	318.61	0.9938	-0.1603
35	0.00	0.00	38.53	273.31	0.9915	-1.1000
36	4537.46	263.68	2842.12	258.14	1.0000	-0.4481
37	2489.19	0.00	1582.25	805.53	0.9832	-0.6905
38	0.00	0.00	7165.16	-289.79	0.9851	-0.3462
39	0.00	0.00	3801.66	1209.42	0.9804	-0.0728
40	0.00	0.00	864.57	155.92	0.9506	-0.6084
41	7633.40	0.00	218.20	286.75	0.9784	-0.7766
42	0.00	0.00	4337.71	-616.93	0.9934	-0.5209
43	0.00	1592.15	1045.60	-495.29	1.0000	-0.2207

Table A.9: Load-flow solution for the 66-bus and 124-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
44	0.00	0.00	2663.27	690.91	0.9812	-0.1454
45	0.00	0.00	52.94	17.40	0.9829	-0.1120
46	0.00	0.00	389.42	128.00	0.9704	-0.3073
47	1399.94	0.00	1174.66	778.94	0.9562	-0.5099
48	0.00	0.00	3136.70	-297.89	0.9936	-1.1301
49	0.00	273.38	800.06	178.69	1.0000	-1.2928
50	0.00	1012.55	1833.84	287.22	1.0000	-0.5970
51	2776.58	1660.37	16.09	637.62	1.0000	-0.1990
52	0.00	162.10	670.99	124.31	1.0000	-1.1571
53	0.00	0.00	4391.99	1443.58	0.9521	-1.1130
54	0.00	-26.36	2275.91	-584.82	1.0000	-0.4307
55	6677.37	0.00	3001.18	1627.62	0.9521	-0.8639
56	3107.68	0.00	2160.47	618.83	0.9544	-0.1990
57	0.00	0.00	620.77	2542.14	0.9737	-0.3019
58	0.00	0.00	1353.37	444.83	0.9639	-1.0874
59	0.00	0.00	1298.54	275.39	0.9865	-0.2842
60	0.00	76.27	556.31	96.21	1.0000	-0.7385
61	0.00	-23.53	3277.63	-480.87	1.0000	-0.5638
62	0.00	0.00	186.93	542.44	0.9850	-0.2680
63	0.00	0.00	472.92	155.44	0.9928	-0.1676
64	0.00	453.22	542.26	178.23	1.0000	-1.1744
65	0.00	753.29	2703.55	888.61	1.0000	-0.6499
66	0.00	0.00	1587.85	763.91	0.9570	-0.3598

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows.

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
1	1 - 2	-1240.76	274.25	19.55	-0.2116	-0.0358	0.0701
2	2 - 3	-4841.57	-495.69	19.55	-0.6191	-0.1415	0.2024
3	3 - 4	8647.45	-1663.50	19.55	0.4423	0.1617	0.1457
4	4 - 5	5925.29	-7.13	19.55	0.3031	0.1385	0.0980
5	5 - 6	510.88	-1040.93	19.55	0.0523	0.0155	0.0391
6	6 - 1	-7589.34	-2469.32	19.55	-0.4313	-0.1380	0.1489
7	2 - 7	3042.96	-314.45	19.55	0.3891	0.1801	0.1272
8	2 - 8	142.21	7.62	8.22	0.0865	0.0010	0.0295
9	1 - 8	234.51	-112.37	8.22	0.1426	0.0542	0.0536
10	3 - 9	3813.55	1281.60	19.55	0.9753	0.1616	0.3328
11	7 - 10	717.90	-103.02	19.55	0.1836	0.0388	0.0611
12	8 - 11	150.44	-16.18	3.18	0.2365	0.1085	0.0873
13	6 - 12	5793.50	1978.88	19.55	0.9878	0.1524	0.3425
14	1 - 13	375.33	80.34	8.22	0.2283	0.0242	0.0791
15	12 - 13	1852.99	91.30	8.22	0.4508	0.1050	0.1594
16	8 - 13	4017.48	331.94	8.22	1.6291	0.9317	0.5541
17	4 - 14	776.30	-484.41	19.55	0.1985	0.0879	0.0756
18	4 - 15	1261.51	-776.23	19.55	0.3226	0.2397	0.1224
19	15 - 16	593.50	-201.35	19.55	0.1518	0.0347	0.0512
20	8 - 17	762.19	215.49	8.22	0.4636	0.0301	0.1633
21	17 - 11	1242.85	286.84	4.05	0.6138	0.0525	0.2048
22	8 - 18	352.99	-161.06	8.22	0.2147	0.0880	0.0800
23	10 - 18	275.46	-83.57	8.22	0.1676	0.0331	0.0606
24	18 - 11	270.18	-6.25	4.05	0.2224	0.0740	0.0719

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows(continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
25	13 - 19	1238.96	-351.86	9.65	0.6419	0.6879	0.2578
26	11 - 20	281.61	20.97	4.05	0.3477	0.0980	0.1173
27	17 - 20	268.85	-31.71	4.05	0.3319	0.2203	0.1087
28	7 - 18	304.37	-81.96	8.22	0.1851	0.0404	0.0662
29	7 - 21	643.25	-462.35	19.55	0.1645	0.0681	0.0667
30	1 - 22	149.50	-74.38	8.22	0.0909	0.0236	0.0344
31	5 - 22	523.30	-63.95	8.22	0.3183	0.0479	0.1109
32	2 - 22	288.06	-123.39	8.22	0.1752	0.0759	0.0650
33	19 - 23	743.84	-260.16	8.22	0.4525	0.3981	0.1625
34	6 - 22	302.43	-88.42	8.22	0.1840	0.0472	0.0659
35	4 - 22	265.09	-189.54	8.22	0.1612	0.0991	0.0671
36	17 - 13	3108.20	59.67	8.22	1.2604	0.8852	0.4293
37	15 - 24	505.60	-18.09	19.55	0.1293	0.0137	0.0413
38	10 - 21	1416.10	-889.11	19.55	0.3622	0.0290	0.1411
39	14 - 24	1192.05	-592.88	19.55	0.3049	0.1698	0.1096
40	17 - 25	786.10	-147.86	9.65	0.4073	0.2643	0.1609
41	25 - 20	213.69	10.36	4.05	0.2638	0.0677	0.0874
42	5 - 26	4278.11	-160.10	19.55	0.4377	0.2150	0.1445
43	6 - 26	1223.11	-205.35	19.55	0.3128	0.1984	0.1041
44	14 - 27	1595.90	-405.32	19.55	0.4082	0.2588	0.1355
45	8 - 28	51.31	6.99	3.18	0.0807	0.0048	0.0299
46	7 - 28	205.79	-61.30	4.05	0.2541	0.1304	0.0874
47	18 - 28	190.48	86.61	4.05	0.1176	0.0022	0.0418

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows(continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
48	21 - 29	1656.62	-642.93	19.55	0.4237	0.3590	0.1489
49	12 - 30	399.32	-251.21	19.55	0.1021	0.0248	0.0407
50	2 - 28	461.12	-4.91	4.05	0.3795	0.1383	0.1235
51	30 - 31	287.24	-0.12	8.22	0.1747	0.0242	0.0616
52	1 - 32	128.35	-38.17	8.22	0.0781	0.0117	0.0276
53	6 - 32	163.87	-99.59	8.22	0.0997	0.0282	0.0401
54	10 - 33	672.80	-472.52	19.55	0.1721	0.0739	0.0694
55	33 - 18	454.69	-69.53	8.22	0.1844	0.0136	0.0642
56	27 - 34	756.52	-5.15	19.55	0.1935	0.0298	0.0628
57	23 - 35	330.73	-102.17	8.22	0.2012	0.0635	0.0719
58	17 - 36	1462.32	-404.86	8.22	0.5930	0.5250	0.2095
59	21 - 33	2001.99	80.45	19.55	0.5120	0.0453	0.1679
60	36 - 19	3537.46	252.31	8.22	1.4345	0.9954	0.4875
61	25 - 36	950.68	-315.89	8.22	0.5783	0.2847	0.2111
62	13 - 37	1416.62	-14.25	8.22	0.4308	0.1842	0.1461
63	32 - 13	1717.13	-55.73	8.22	1.0445	0.9076	0.3555
64	37 - 19	1489.19	-217.10	8.22	0.9058	0.4620	0.3156
65	22 - 38	695.32	-111.00	8.22	0.4229	0.2491	0.1452
66	2 - 38	1494.62	155.49	8.22	0.3637	0.0632	0.1246
67	3 - 38	1745.47	205.09	8.22	0.3539	0.0762	0.1208
68	4 - 38	3241.32	601.89	8.22	0.4929	0.0407	0.1698
69	7 - 39	650.13	47.75	19.55	0.1663	0.0171	0.0549
70	9 - 39	2917.90	-442.72	19.55	0.7463	0.1705	0.2508

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows(continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
71	3 - 39	1366.61	-600.62	19.55	0.3495	0.3274	0.1235
72	20 - 40	223.06	-110.30	4.05	0.2754	0.1870	0.1046
73	25 - 40	248.56	-43.32	4.05	0.3069	0.1924	0.1030
74	37 - 41	544.34	-170.51	8.22	0.3311	0.1923	0.1196
75	31 - 41	1328.98	71.32	8.22	0.8084	0.3551	0.2744
76	41 - 19	850.58	-321.40	8.22	0.5174	0.2654	0.1916
77	36 - 42	548.34	-134.95	8.22	0.3335	0.1681	0.1164
78	25 - 42	3828.35	-158.52	8.22	2.3287	0.4462	0.8076
79	26 - 43	1832.44	-1324.59	19.55	0.4687	0.1406	0.1945
80	41 - 23	6633.40	203.98	8.22	2.6899	0.6582	0.9325
81	39 - 44	1116.90	-469.66	19.55	0.2857	0.1575	0.1022
82	21 - 44	1552.02	-52.78	19.55	0.3969	0.1077	0.1301
83	14 - 45	52.94	11.69	8.22	0.0322	0.0005	0.0111
84	6 - 43	2296.87	-611.62	19.55	0.5874	0.3483	0.1995
85	28 - 46	390.52	114.22	3.18	0.6140	0.0664	0.2393
86	11 - 47	147.81	-12.58	3.18	0.2324	0.0670	0.0890
87	18 - 47	249.32	-22.08	4.05	0.3078	0.1765	0.1000
88	47 - 20	136.42	26.22	3.18	0.2145	0.0344	0.0838
89	35 - 48	291.75	-164.75	8.22	0.1775	0.0685	0.0697
90	23 - 48	585.43	-146.09	8.22	0.3561	0.1323	0.1253
91	31 - 49	408.72	138.14	3.18	0.6426	0.0211	0.2490
92	33 - 47	1024.45	204.60	4.05	0.6324	0.1343	0.2119
93	47 - 50	1103.59	-708.13	4.05	0.6812	0.1986	0.2740

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows(continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
94	12 - 32	208.83	-132.48	8.22	0.0847	0.0045	0.0354
95	12 - 51	1854.17	-1376.78	19.55	0.4742	0.1422	0.1990
96	51 - 43	1560.60	-145.08	19.55	0.3991	0.0490	0.1296
97	37 - 52	284.39	45.85	3.18	0.4472	0.0381	0.1691
98	41 - 52	389.42	-83.38	4.05	0.3205	0.1777	0.1084
99	19 - 53	4440.38	-4.09	8.22	0.6002	0.4752	0.2035
100	47 - 40	399.94	-35.93	3.18	0.6288	0.2308	0.2423
101	43 - 54	133.45	-70.72	8.22	0.0812	0.0194	0.0311
102	33 - 50	745.92	6.17	4.05	0.4604	0.2057	0.1513
103	41 - 55	1402.80	258.50	8.22	0.5689	0.1912	0.2004
104	55 - 49	395.26	-136.26	4.05	0.3253	0.2446	0.1170
105	26 - 56	1162.36	-59.87	19.55	0.2973	0.0926	0.1001
106	55 - 48	2291.92	-465.32	8.22	0.9294	0.5686	0.3376
107	43 - 57	3948.15	966.03	19.55	0.6732	0.1807	0.2242
108	55 - 23	2385.45	-567.05	8.22	0.9673	0.4506	0.3540
109	19 - 58	1366.35	-85.59	8.22	0.5541	0.4248	0.1882
110	57 - 54	226.83	-98.10	8.22	0.1380	0.0268	0.0523
111	29 - 59	614.98	-261.24	19.55	0.1573	0.0445	0.0560
112	51 - 57	1776.58	54.27	19.55	0.4544	0.2284	0.1470
113	54 - 60	190.92	11.70	3.18	0.3002	0.0413	0.1104
114	56 - 54	2107.68	-237.40	8.22	0.3663	0.0194	0.1309
115	57 - 61	159.14	-103.45	8.22	0.0968	0.0311	0.0402
116	30 - 61	1854.19	88.79	8.22	0.5639	0.1031	0.1991

Table A.10: Load-flow solution for 66-bus and 124-line network - line flows(continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
117	29 - 62	871.48	223.07	19.55	0.2229	0.0089	0.0754
118	51 - 61	1271.24	60.57	8.22	0.3866	0.0912	0.1312
119	34 - 63	473.05	-70.08	19.55	0.1210	0.0162	0.0398
120	62 - 59	684.41	-256.04	19.55	0.1750	0.0355	0.0614
121	43 - 64	542.32	274.85	8.22	0.3299	0.0049	0.1254
122	57 - 65	2738.08	-708.63	19.55	0.7003	0.7247	0.2403
123	57 - 66	1960.45	369.33	19.55	0.5014	0.1232	0.1695
124	66 - 60	368.23	-120.98	4.05	0.3031	0.1910	0.1079

A.3 A 66-bus Network with 97 lines

Again, this network was developed from a 6-bus core ring network, by adding sixty new buses. The mesh density requirements were very high, requiring that after every new bus was placed, a new loop connection was attempted. However, the new generation was restricted, and no new generating sites were allowed. This limited resulted in a network which was not fully developed - all buses were added, but only 97 lines (in comparison with the 121 from the previous example) were successfully placed.

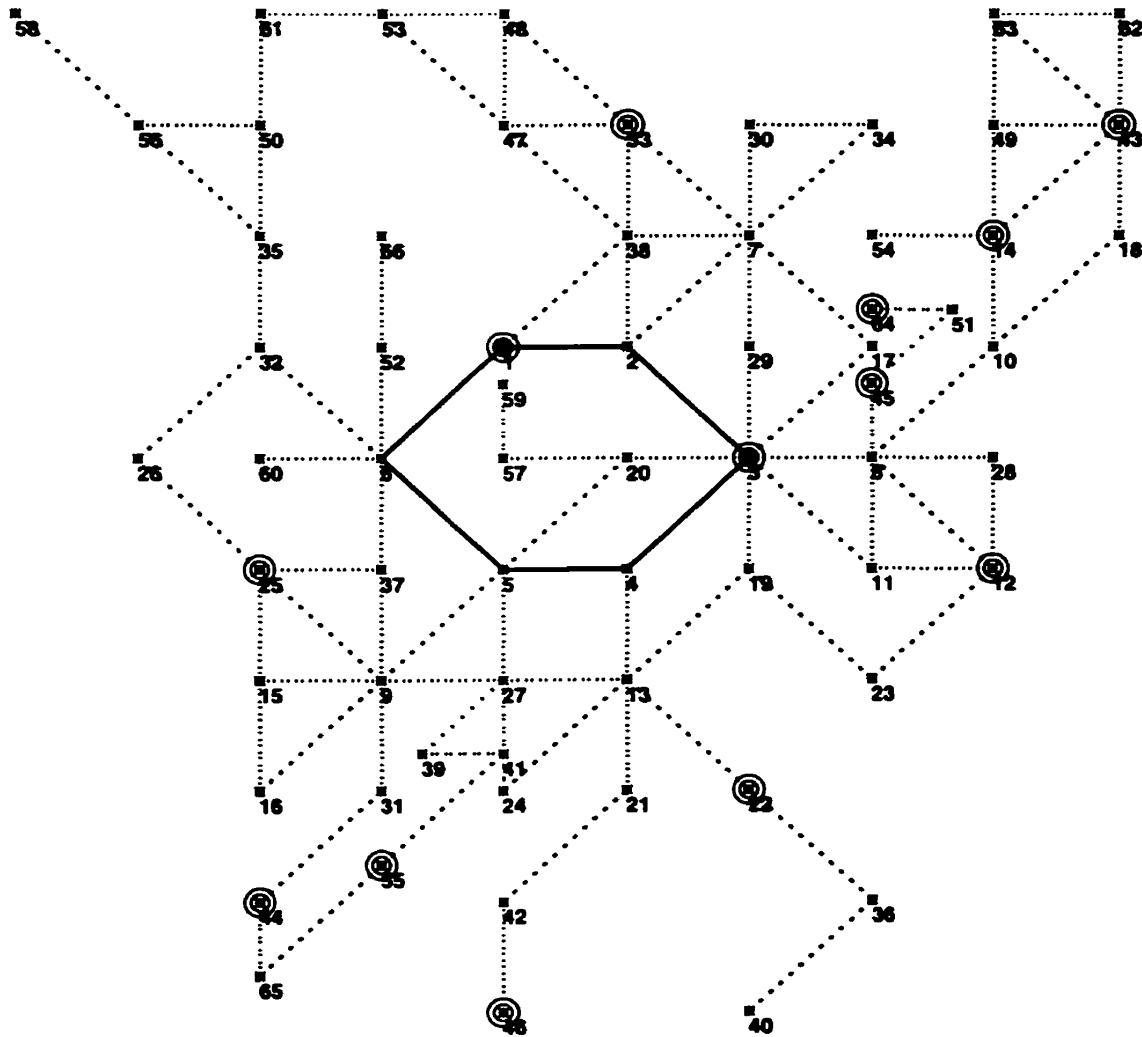


Figure A.6: A 66-bus network with 97 lines - network layout.

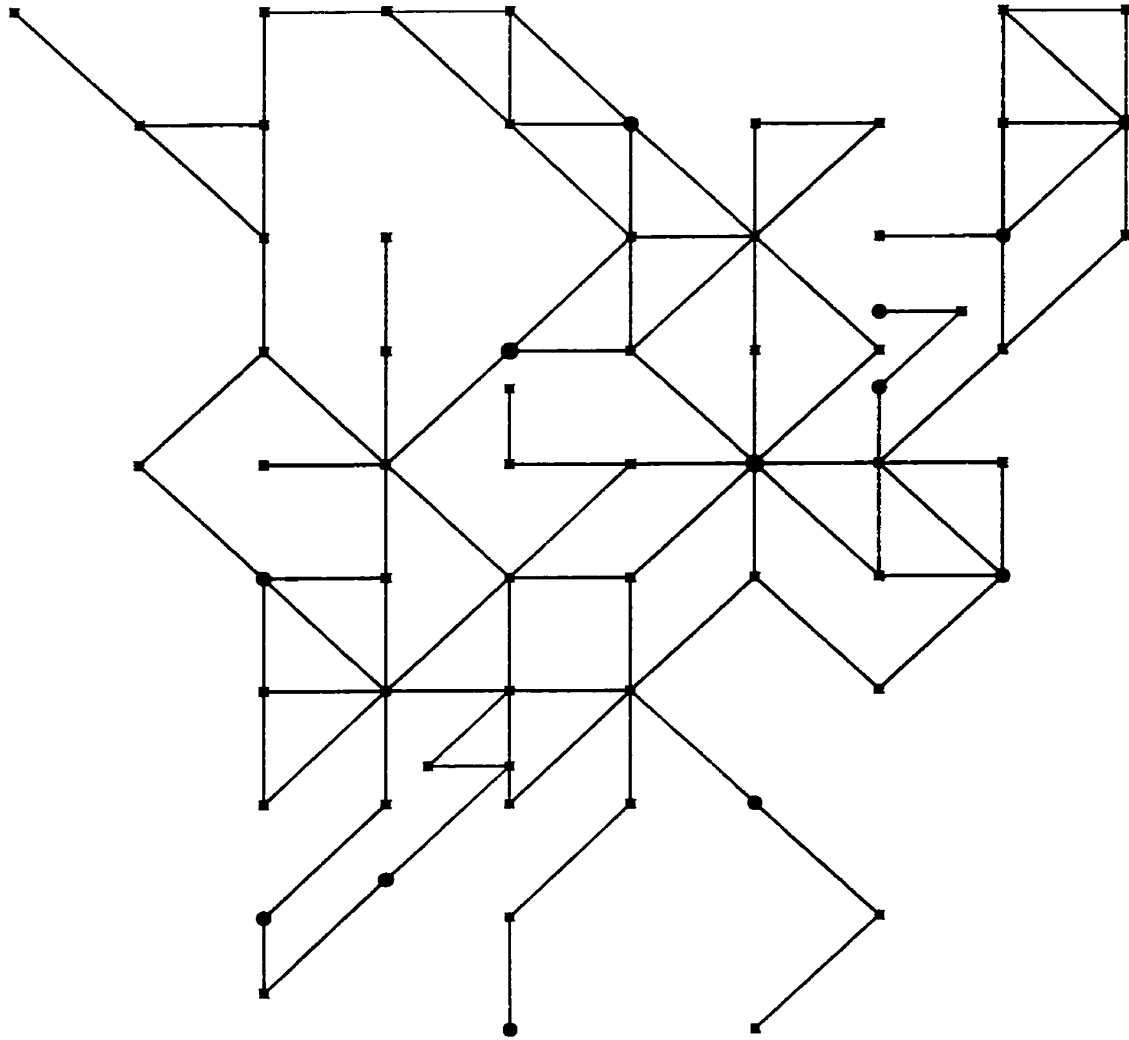


Figure A.7: A 66-bus network with 97 lines - topology layout.

Line Data

Table A.11: Line data for network of 66 buses and 97 lines.

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the Line (km)
				R (Ω)	X (Ω)	B (mS)			
1	1 - 2	735	3	0.2467	6.8907	0.8117	0.00	14.24	59
2	2 - 3	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
3	3 - 4	735	10	0.1600	4.4697	5.8501	0.00	47.48	128
4	4 - 5	735	10	0.2000	5.5871	7.3126	0.00	47.48	160
5	5 - 6	735	5	0.2600	7.2632	2.3766	0.00	23.74	104
6	6 - 1	735	9	0.1556	4.3455	4.6070	0.00	42.73	112
7	2 - 7	735	2	1.0187	28.4592	1.4900	0.00	9.50	163
8	3 - 8	735	4	0.3875	10.8250	2.2669	0.00	18.99	124
9	5 - 9	735	5	0.5625	15.7137	5.1417	0.00	23.74	225
10	8 - 10	735	4	0.6062	16.9358	3.5466	0.00	18.99	194
11	3 - 11	735	2	0.0250	0.6984	0.0366	0.00	9.50	4
12	8 - 12	500	2	0.1581	3.2854	0.1419	375.00	5.60	17
13	11 - 8	735	2	1.4062	39.2842	2.0567	0.00	9.50	225
14	4 - 13	735	2	0.6187	17.2850	0.9049	0.00	9.50	99
15	11 - 12	500	2	1.5812	32.8543	1.4192	187.50	5.60	170
16	10 - 14	735	2	0.7250	20.2532	1.0603	0.00	9.50	116
17	9 - 15	735	2	0.7687	21.4753	1.1243	0.00	9.50	123
18	9 - 16	735	2	0.1500	4.1903	0.2194	0.00	9.50	24
19	3 - 17	735	2	1.3062	36.4906	1.9104	0.00	9.50	209
20	16 - 15	735	2	0.9188	25.6657	1.3437	0.00	9.50	147

Table A.11: Line data for network of 66 buses and 97 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
21	10 - 18	735	2	0.8375	23.3959	1.2249	0.00	9.50	134
22	3 - 19	735	5	0.2225	6.2156	2.0338	0.00	23.74	89
23	19 - 13	735	2	0.8250	23.0467	1.2066	0.00	9.50	132
24	3 - 20	735	4	0.3344	9.3409	1.9561	0.00	18.99	107
25	20 - 5	735	2	0.9562	26.7132	1.3985	0.00	9.50	153
26	13 - 21	735	2	0.6938	19.3802	1.0146	0.00	9.50	111
27	13 - 22	500	2	0.0465	0.9663	0.0417	375.00	5.60	5
28	19 - 23	735	3	0.3708	10.3594	1.2203	0.00	14.24	89
29	13 - 24	735	2	0.5500	15.3645	0.8044	0.00	9.50	88
30	9 - 25	500	2	0.2139	4.4450	0.1920	375.00	5.60	23
31	15 - 25	500	3	0.5829	12.1110	1.1771	75.00	8.40	94
32	23 - 12	500	5	0.0409	0.8503	0.2296	46.88	14.00	11
33	25 - 26	500	2	0.0186	0.3865	0.0167	0.00	5.60	2
34	13 - 27	735	2	0.7375	20.6024	1.0786	0.00	9.50	118
35	5 - 27	735	2	0.5625	15.7137	0.8227	0.00	9.50	90
36	27 - 9	735	2	0.5500	15.3645	0.8044	0.00	9.50	88
37	8 - 28	735	2	0.4250	11.8725	0.6216	0.00	9.50	68
38	3 - 29	735	6	0.2542	7.1002	3.3455	0.00	28.49	122
39	29 - 7	735	2	0.5938	16.5866	0.8684	0.00	9.50	95
40	7 - 30	735	2	0.3938	10.9996	0.5759	0.00	9.50	63
41	17 - 7	735	2	1.3812	38.5858	2.0201	0.00	9.50	221
42	9 - 31	735	3	0.8917	24.9091	2.9342	0.00	14.24	214

Table A.11: Line data for network of 66 buses and 97 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
43	6 - 32	735	6	0.4521	12.6291	5.9507	0.00	28.49	217
44	32 - 26	500	3	0.8371	17.3935	1.6905	93.75	8.40	135
45	28 - 12	500	2	0.3907	8.1170	0.3506	93.75	5.60	42
46	7 - 33	735	3	1.0917	30.4961	3.5923	0.00	14.24	262
47	7 - 34	735	2	0.5000	13.9677	0.7313	0.00	9.50	80
48	32 - 35	735	2	1.3375	37.3636	1.9561	0.00	9.50	214
49	22 - 36	500	2	1.2650	26.2835	1.1354	0.00	5.60	136
50	9 - 37	735	2	0.8562	23.9197	1.2523	0.00	9.50	137
51	30 - 34	735	2	0.5187	14.4915	0.7587	0.00	9.50	83
52	6 - 37	735	2	1.8062	50.4583	2.6417	0.00	9.50	289
53	7 - 38	500	2	0.7069	14.6878	0.6345	375.00	5.60	76
54	2 - 38	500	4	0.3534	7.3439	1.2690	62.50	11.20	76
55	1 - 38	500	2	2.2881	47.5422	2.0537	187.50	5.60	246
56	37 - 25	500	3	0.9239	19.1972	1.8659	125.00	8.40	149
57	27 - 39	735	2	0.6750	18.8564	0.9872	0.00	9.50	108
58	36 - 40	345	2	2.7357	28.7882	0.8196	179.00	2.90	121
59	27 - 41	500	2	1.0231	21.2587	0.9183	375.00	5.60	110
60	24 - 41	500	2	1.7951	37.2993	1.6112	187.50	5.60	193
61	21 - 42	735	2	0.5688	15.8883	0.8318	0.00	9.50	91
62	39 - 41	500	2	0.9208	19.1328	0.8265	125.00	5.60	99
63	14 - 43	500	2	0.6883	14.3013	0.6178	375.00	5.60	74
64	18 - 43	500	3	0.9301	19.3261	1.8784	125.00	8.40	150

Table A.11: Line data for network of 66 buses and 97 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
65	31 - 44	500	2	0.0279	0.5798	0.0250	375.00	5.60	3
66	8 - 45	500	2	0.2325	4.8315	0.2087	375.00	5.60	25
67	42 - 46	500	2	0.1116	2.3191	0.1002	375.00	5.60	12
68	38 - 47	500	2	0.6697	13.9148	0.6011	0.00	5.60	72
69	33 - 38	500	2	0.0837	1.7393	0.0751	93.75	5.60	9
70	33 - 48	735	2	0.9350	26.1196	1.3675	0.00	9.50	150
71	14 - 49	735	2	1.1062	30.9035	1.6179	0.00	9.50	177
72	49 - 43	500	3	0.8991	18.6819	1.8158	125.00	8.40	145
73	35 - 50	500	2	0.3534	7.3439	0.3172	375.00	5.60	38
74	45 - 51	500	2	1.0882	22.6115	0.9768	0.00	5.60	117
75	6 - 52	735	2	0.5375	15.0153	0.7861	0.00	9.50	86
76	33 - 47	500	2	0.3907	8.1170	0.3506	125.00	5.60	42
77	47 - 53	500	2	2.2044	45.8028	1.9786	0.00	5.60	237
78	48 - 53	500	3	0.4837	10.0496	0.9768	125.00	8.40	78
79	14 - 54	735	2	0.5562	15.5391	0.8135	0.00	9.50	89
80	41 - 55	345	2	0.1809	1.9034	0.0542	179.00	2.90	8
81	48 - 47	500	6	0.0186	0.3865	0.1503	37.50	16.80	6
82	35 - 56	735	2	0.6250	17.4596	0.9141	0.00	9.50	100
83	20 - 57	735	3	0.6833	19.0892	2.2486	0.00	14.24	164
84	56 - 58	500	2	0.4744	9.8563	0.4258	375.00	5.60	51
85	56 - 50	500	2	0.5953	12.3687	0.5343	125.00	5.60	64
86	57 - 59	735	2	1.3750	38.4112	2.0110	0.00	9.50	220

Table A.11: Line data for network of 66 buses and 97 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
87	6 - 60	735	2	0.0500	1.3968	0.0731	0.00	9.50	8
88	50 - 61	345	2	4.0696	42.8255	1.2192	179.00	2.90	180
89	53 - 61	345	2	1.0337	12.6750	0.5882	59.67	4.19	68
90	43 - 62	500	2	2.3811	49.4748	2.1372	0.00	5.60	256
91	43 - 63	500	2	2.1858	45.4163	1.9619	0.00	5.60	235
92	63 - 62	500	2	0.3814	7.9237	0.3423	0.00	5.60	41
93	51 - 64	345	2	0.0904	0.9517	0.0271	179.00	2.90	4
94	49 - 63	500	2	2.7532	57.2052	2.4711	187.50	5.60	296
95	55 - 65	345	2	2.7667	33.9243	1.5744	0.00	4.19	182
96	44 - 65	345	2	1.0185	12.4886	0.5796	89.50	4.19	67
97	52 - 66	500	2	0.9301	19.3261	0.8348	375.00	5.60	100

Bus Data

Table A.12: Voltage regulated bus data for network of 66 buses and 97 lines.

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MW)	Q_{gmin} (MVar)	Q_{gmax} (MVar)	P_d (MW)	Q_d (MVar)
1	1.0000	13500.00	7266.12	0.00	1077.00	568.70	496.62
3	1.0000	48200.00	48168.64	0.00	3618.00	10500.00	1479.08
12	1.0000	0.00	0.00	-50.00	224.00	1061.17	53.06
14	1.0000	0.00	0.00	0.00	1584.00	114.01	1403.71
22	1.0000	0.00	0.00	-50.00	269.00	103.52	311.31
25	1.0000	0.00	0.00	0.00	476.00	1020.47	51.02
33	1.0000	0.00	0.00	0.00	1176.00	2812.37	1702.98
43	1.0000	0.00	0.00	-30.00	50.00	447.86	890.55
44	1.0000	0.00	0.00	-50.00	243.00	229.15	147.64
45	1.0000	0.00	0.00	-50.00	276.00	47.39	248.90
46	1.0000	0.00	0.00	-50.00	290.00	395.10	129.86
55	1.0000	0.00	0.00	-50.00	200.00	144.38	227.61
64	1.0000	0.00	0.00	-50.00	151.00	258.62	85.00

Table A.13: Load (PQ) bus data

Bus No	P_d (MW)	Q_d (MVA _r)
2	749.49	1221.85
4	819.64	631.45
5	757.73	5680.07
6	135.98	3901.23
7	105.46	2862.86
8	101.35	2151.26
9	318.44	2137.31
10	1045.30	2876.40
11	35.64	868.25
13	173.78	1105.19
15	1870.64	1143.11
16	144.28	524.63
17	12.01	531.90
18	77.59	395.96
19	906.19	1482.70
20	1738.70	2263.34
21	277.75	514.35
23	3598.10	1571.15
24	180.88	330.51
26	1697.62	232.30

Table A.13: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
27	136.04	1218.69
28	642.63	397.91
29	4049.56	2290.61
30	15.48	264.46
31	1521.83	538.91
32	3419.00	2446.02
34	961.27	445.09
35	332.61	637.86
36	138.53	111.60
37	1355.03	972.06
38	750.35	7.02
39	85.76	248.36
40	129.34	42.51
41	515.63	163.26
42	188.18	81.92
47	805.38	792.32
48	68.92	74.70
49	59.41	712.61
50	211.57	147.67
51	85.51	62.92

Table A.13: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
52	389.43	299.45
53	604.46	385.28
54	490.90	161.35
56	80.58	224.79
57	1133.26	1219.46
58	119.07	39.14
59	1333.52	438.31
60	806.74	265.16
61	426.60	20.50
62	926.25	109.02
63	408.25	508.90
65	275.47	78.10
66	163.32	53.68

Load-Flow Solution

Table A.14: Load-flow solution for the 66-bus and 97-line network.

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
1**	7266.12	1076.30	568.70	496.62	1.0000	0.0000
2	0.00	0.00	749.49	1221.85	0.9944	0.0161
3	48168.64	3617.51	10500.00	1479.08	1.0000	0.0791
4	0.00	0.00	819.64	631.45	1.0007	0.0075
5	0.00	0.00	757.73	5680.07	0.9800	-0.0543
6	0.00	0.00	135.98	3901.23	0.9856	-0.0616
7	0.00	0.00	105.46	2862.86	0.9780	-0.0748
8	0.00	0.00	101.35	2151.26	0.9783	-0.0035
9	0.00	0.00	318.44	2137.31	0.9710	-0.1710
10	0.00	0.00	1045.30	2876.40	0.9572	-0.1236
11	0.00	0.00	35.64	868.25	0.9994	0.0773
12	0.00	203.00	1061.17	53.06	1.0000	-0.1550
13	0.00	0.00	173.78	1105.19	0.9843	-0.0530
14	0.00	1583.33	114.01	1403.71	1.0000	-0.1964
15	0.00	0.00	1870.64	1143.11	0.9551	-0.2414
16	0.00	0.00	144.28	524.63	0.9676	-0.1817
17	0.00	0.00	12.01	531.90	1.0050	0.0040
18	0.00	0.00	77.59	395.96	0.9584	-0.1579
19	0.00	0.00	906.19	1482.70	0.9767	0.0062
20	0.00	0.00	1738.70	2263.34	0.9721	-0.0103

**Bus number 1 is selected as a slack and a reference bus for this presented load-flow solution

Table A.14: Load-flow solution for the 66-bus and 97-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVar)	P_d (MW)	Q_d (MVar)		
21	0.00	0.00	277.75	514.35	0.9820	-0.0850
22	0.00	243.68	103.52	311.31	1.0000	-0.6579
23	0.00	0.00	3598.10	1571.15	0.9501	-0.0757
24	0.00	0.00	180.88	330.51	0.9852	-0.0673
25	0.00	475.71	1020.47	51.02	1.0000	-0.5942
26	0.00	0.00	1697.62	232.30	0.9995	-0.5955
27	0.00	0.00	136.04	1218.69	0.9753	-0.1047
28	0.00	0.00	642.63	397.91	0.9739	-0.0253
29	0.00	0.00	4049.56	2290.61	0.9775	-0.0044
30	0.00	0.00	15.48	264.46	0.9784	-0.0823
31	0.00	0.00	1521.83	538.91	0.9703	-0.2622
32	0.00	0.00	3419.00	2446.02	0.9687	-0.1882
33	0.00	1175.80	2812.37	1702.98	1.0000	-0.2921
34	0.00	0.00	961.27	445.09	0.9768	-0.0917
35	0.00	0.00	332.61	637.86	0.9798	-0.2529
36	0.00	0.00	138.53	111.60	1.0040	-0.6862
37	0.00	0.00	1355.03	972.06	0.9753	-0.1991
38	0.00	0.00	750.35	7.02	0.9943	-0.3181
39	0.00	0.00	85.76	248.36	0.9782	-0.1219
40	0.00	0.00	129.34	42.51	0.9824	-0.9173
41	0.00	0.00	515.63	163.26	1.0000	-0.3480
42	0.00	0.00	188.18	81.92	0.9820	-0.1028
43	0.00	39.21	447.86	890.55	1.0000	-0.5576

Table A.14: Load-flow solution for the 66-bus and 97-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
44	0.00	220.11	229.15	147.64	1.0000	-0.8068
45	0.00	250.51	47.39	248.90	1.0000	-0.6584
46	0.00	263.13	395.10	129.86	1.0000	-0.7555
47	0.00	0.00	805.38	792.32	0.9764	-0.3722
48	0.00	0.00	68.92	74.70	1.0056	-0.3247
49	0.00	0.00	59.41	712.61	1.0032	-0.2524
50	0.00	0.00	211.57	147.67	0.9759	-0.4111
51	0.00	0.00	85.51	62.92	0.9988	-0.6896
52	0.00	0.00	389.43	299.45	0.9856	-0.0775
53	0.00	0.00	604.46	385.28	0.9710	-0.4890
54	0.00	0.00	490.90	161.35	1.0011	-0.2105
55	0.00	181.14	144.38	227.61	1.0000	-0.8477
56	0.00	0.00	80.58	224.79	0.9822	-0.2681
57	0.00	0.00	1133.26	1219.46	0.9550	-0.1042
58	0.00	0.00	119.07	39.14	0.9834	-0.4591
59	0.00	0.00	1333.52	438.31	0.9500	-0.2090
60	0.00	0.00	806.74	265.16	0.9849	-0.0637
61	0.00	0.00	426.60	20.50	0.9872	-0.6757
62	0.00	0.00	926.25	109.02	1.0130	-0.6542
63	0.00	0.00	408.25	508.90	1.0107	-0.6405
64	0.00	137.05	258.62	85.00	1.0000	-1.0919
65	0.00	0.00	275.47	78.10	1.0059	-0.8968
66	0.00	0.00	163.32	53.68	1.0445	-0.3306

Table A.15: Load-flow solution for 66-bus and 97-line network - line flows.

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
1	1 - 2	-1240.77	274.24	19.55	-0.2116	-0.0358	0.0789
2	2 - 3	-4841.58	-495.68	19.55	-0.6191	-0.1415	0.2017
3	3 - 4	8647.45	-1663.50	19.55	0.4423	0.1617	0.1452
4	4 - 5	5925.30	-7.14	19.55	0.3031	0.1385	0.1177
5	5 - 6	510.88	-1040.92	19.55	0.0523	0.0155	0.0184
6	6 - 1	-7589.34	-2469.34	19.55	-0.4313	-0.1380	0.1416
7	2 - 7	1688.55	-72.19	19.55	0.4319	0.2011	0.1528
8	3 - 8	4067.80	490.37	19.55	0.5202	0.1842	0.1826
9	5 - 9	3822.12	-945.30	19.55	0.3910	0.2479	0.1415
10	8 - 10	3604.25	-171.50	19.55	0.4609	0.2554	0.1678
11	3 - 11	1392.92	440.83	19.55	0.3562	0.0041	0.1214
12	8 - 12	97.56	-23.63	8.22	0.0593	0.0030	0.0207
13	11 - 8	1095.96	-261.12	19.55	0.2803	0.1777	0.1147
14	4 - 13	1880.36	256.00	19.55	0.4809	0.1360	0.1672
15	11 - 12	261.21	-149.33	8.22	0.1589	0.0796	0.0685
16	10 - 14	1818.08	-1352.84	19.55	0.4650	0.1541	0.1726
17	9 - 15	1655.63	101.29	19.55	0.4234	0.1488	0.1523
18	9 - 16	1314.16	335.89	19.55	0.3361	0.0230	0.1183
19	3 - 17	1112.84	-588.48	19.55	0.2846	0.1679	0.0991
20	16 - 15	1169.32	-92.86	19.55	0.2991	0.1256	0.1118
21	10 - 18	725.00	-344.13	19.55	0.1854	0.0710	0.0666
22	3 - 19	6256.27	1474.49	19.55	0.6400	0.1627	0.2238
23	19 - 13	1327.06	-492.88	19.55	0.3394	0.1280	0.1129
24	3 - 20	5077.80	1128.84	19.55	0.6493	0.1984	0.2286

Table A.15: Load-flow solution for 66-bus and 97-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
25	20 - 5	841.07	-524.08	19.55	0.2151	0.0940	0.0734
26	13 - 21	862.47	-219.06	19.55	0.2206	0.0699	0.0771
27	13 - 22	372.19	100.75	8.22	0.2264	0.0033	0.0814
28	19 - 23	4005.21	1060.66	19.55	0.6829	0.1736	0.2454
29	13 - 24	484.81	-255.19	19.55	0.1240	0.0312	0.0431
30	9 - 25	262.78	15.12	8.22	0.1598	0.0108	0.0573
31	15 - 25	947.35	-94.86	8.22	0.3842	0.1065	0.1386
32	23 - 12	394.20	-258.94	8.22	0.0959	0.0031	0.0387
33	25 - 26	837.01	272.12	8.22	0.5091	0.0030	0.1817
34	13 - 27	1306.97	-61.48	19.55	0.3343	0.1127	0.1177
35	5 - 27	1659.83	-71.50	19.55	0.4245	0.1091	0.1433
36	27 - 9	2210.59	-66.79	19.55	0.5654	0.1421	0.1898
37	8 - 28	952.24	14.33	19.55	0.2435	0.0473	0.0854
38	3 - 29	6261.02	839.28	19.55	0.5338	0.1860	0.1874
39	29 - 7	2191.59	-239.25	19.55	0.5605	0.1521	0.1863
40	7 - 30	351.87	-179.40	19.55	0.0900	0.0162	0.0314
41	17 - 7	1097.83	-167.12	19.55	0.2808	0.1750	0.1187
42	9 - 31	1862.53	-713.53	19.55	0.3176	0.1918	0.1147
43	6 - 32	5187.95	-706.95	19.55	0.4423	0.2707	0.1601
44	32 - 26	863.36	-93.87	8.22	0.3501	0.1393	0.1298
45	28 - 12	308.84	-85.18	8.22	0.1879	0.0233	0.0654
46	7 - 33	3730.28	-1035.81	19.55	0.6360	0.4674	0.2154
47	7 - 34	625.47	-161.33	19.55	0.1600	0.0366	0.0560

Table A.15: Load-flow solution for 66-bus and 97-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
48	32 - 35	881.77	-654.76	19.55	0.2255	0.1362	0.0806
49	22 - 36	268.64	-188.99	8.22	0.1634	0.0655	0.0587
50	9 - 37	597.93	-427.06	19.55	0.1529	0.0598	0.0540
51	30 - 34	336.29	-148.84	19.55	0.0860	0.0204	0.0351
52	6 - 37	1416.10	-538.57	19.55	0.3622	0.2924	0.1385
53	7 - 38	150.29	-67.98	8.22	0.0914	0.0205	0.0363
54	2 - 38	1161.95	33.57	8.22	0.3534	0.0792	0.1257
55	1 - 38	331.31	-200.79	8.22	0.2015	0.1438	0.0939
56	37 - 25	651.40	-137.46	8.22	0.2641	0.1160	0.1014
57	27 - 39	466.45	-347.24	19.55	0.1193	0.0368	0.0418
58	36 - 40	129.74	-23.43	3.18	0.2040	0.0809	0.0861
59	27 - 41	148.24	-106.66	8.22	0.0902	0.0292	0.0392
60	24 - 41	303.69	-171.24	8.22	0.1847	0.1051	0.0785
61	21 - 42	583.73	-231.19	19.55	0.1493	0.0388	0.0520
62	39 - 41	380.39	-95.15	8.22	0.2314	0.0675	0.0830
63	14 - 43	227.05	-36.17	8.22	0.1381	0.0301	0.0528
64	18 - 43	646.51	-157.96	8.22	0.2622	0.1159	0.1007
65	31 - 44	334.63	71.27	8.22	0.2035	0.0018	0.0730
66	8 - 45	392.26	94.04	8.22	0.2386	0.0176	0.0881
67	42 - 46	395.18	109.82	8.22	0.2404	0.0085	0.0876
68	38 - 47	957.89	224.68	8.22	0.5827	0.1237	0.2132
69	33 - 38	67.78	6.41	8.22	0.0412	0.0011	0.0149
70	33 - 48	673.73	-498.92	19.55	0.1723	0.0736	0.0592

Table A.15: Load-flow solution for 66-bus and 97-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
71	14 - 49	979.28	-500.53	19.55	0.2505	0.1266	0.0867
72	49 - 43	525.12	-145.43	8.22	0.2129	0.0910	0.0837
73	35 - 50	98.47	-27.87	8.22	0.0599	0.0067	0.0231
74	45 - 51	344.70	-120.02	8.22	0.2097	0.0723	0.0755
75	6 - 52	553.16	-222.06	19.55	0.1415	0.0348	0.0491
76	33 - 47	146.97	5.97	8.22	0.0894	0.0111	0.0359
77	47 - 53	604.69	-200.83	8.22	0.3678	0.2531	0.1399
78	48 - 53	296.02	-35.69	8.22	0.1200	0.0276	0.0497
79	14 - 54	491.16	-271.60	19.55	0.1256	0.0319	0.0429
80	41 - 55	315.35	76.91	3.18	0.4958	0.0130	0.1882
81	48 - 47	307.98	182.22	8.22	0.0624	0.0011	0.0259
82	35 - 56	448.58	-320.84	19.55	0.1147	0.0328	0.0400
83	20 - 57	2480.37	-76.08	19.55	0.4229	0.1981	0.1533
84	56 - 58	119.10	-40.86	8.22	0.0724	0.0109	0.0282
85	56 - 50	248.66	-36.56	8.22	0.1512	0.0285	0.0557
86	57 - 59	1338.54	-407.02	19.55	0.3423	0.2124	0.1265
87	6 - 60	806.80	228.71	19.55	0.2063	0.0047	0.0713
88	50 - 61	135.38	-59.49	3.18	0.2129	0.1256	0.0926
89	53 - 61	292.67	-35.68	4.05	0.3613	0.0778	0.1211
90	43 - 62	490.42	-332.40	8.22	0.2983	0.2212	0.1094
91	43 - 63	457.54	-307.26	8.22	0.2783	0.1900	0.1016
92	63 - 62	438.47	-132.80	8.22	0.2667	0.0322	0.0899
93	51 - 64	258.67	50.21	3.18	0.4067	0.0053	0.1526

Table A.15: Load-flow solution for 66-bus and 97-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
94	49 - 63	392.78	-245.96	8.22	0.2389	0.2037	0.1117
95	55 - 65	170.81	-124.01	4.05	0.2109	0.1216	0.0728
96	44 - 65	105.46	-37.66	4.05	0.1302	0.0276	0.0440
97	52 - 66	163.42	-117.73	8.22	0.0994	0.0293	0.0385

A.4 A 330-bus Network with 430 lines

In addition to a set of relatively smaller power system networks, an example of 330-bus and 430 line network is presented. This network was developed from a 30-bus core ring network, by adding three hundred and thirty new buses. The mesh density requirements were moderate, requiring one new loop connection to be added after three new buses were placed. Also, the new generation was not limited. The network was developed in full, having all desired 330 buses and 430 lines.

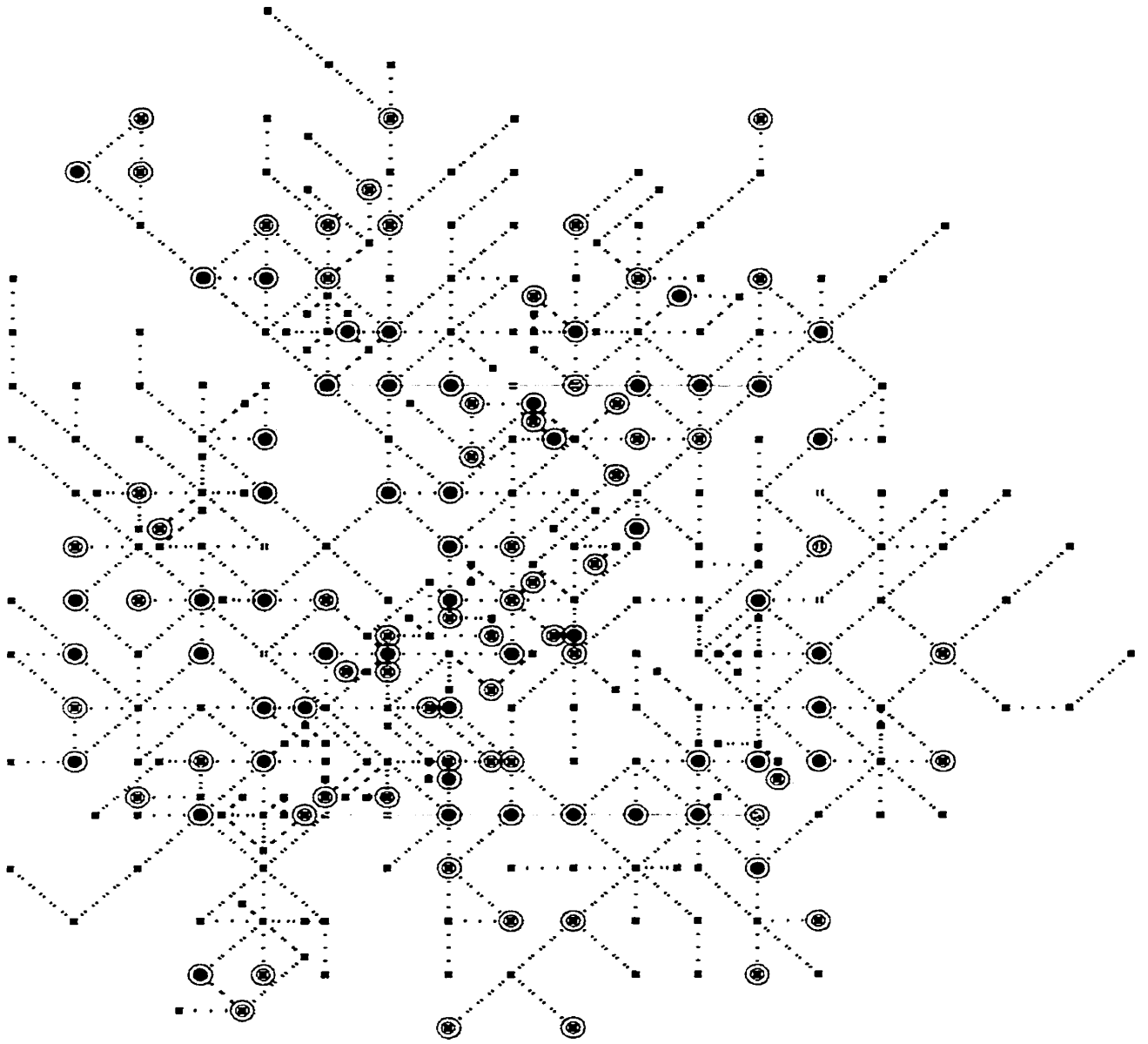


Figure A.8: A 330-bus network with 430 lines - network layout.

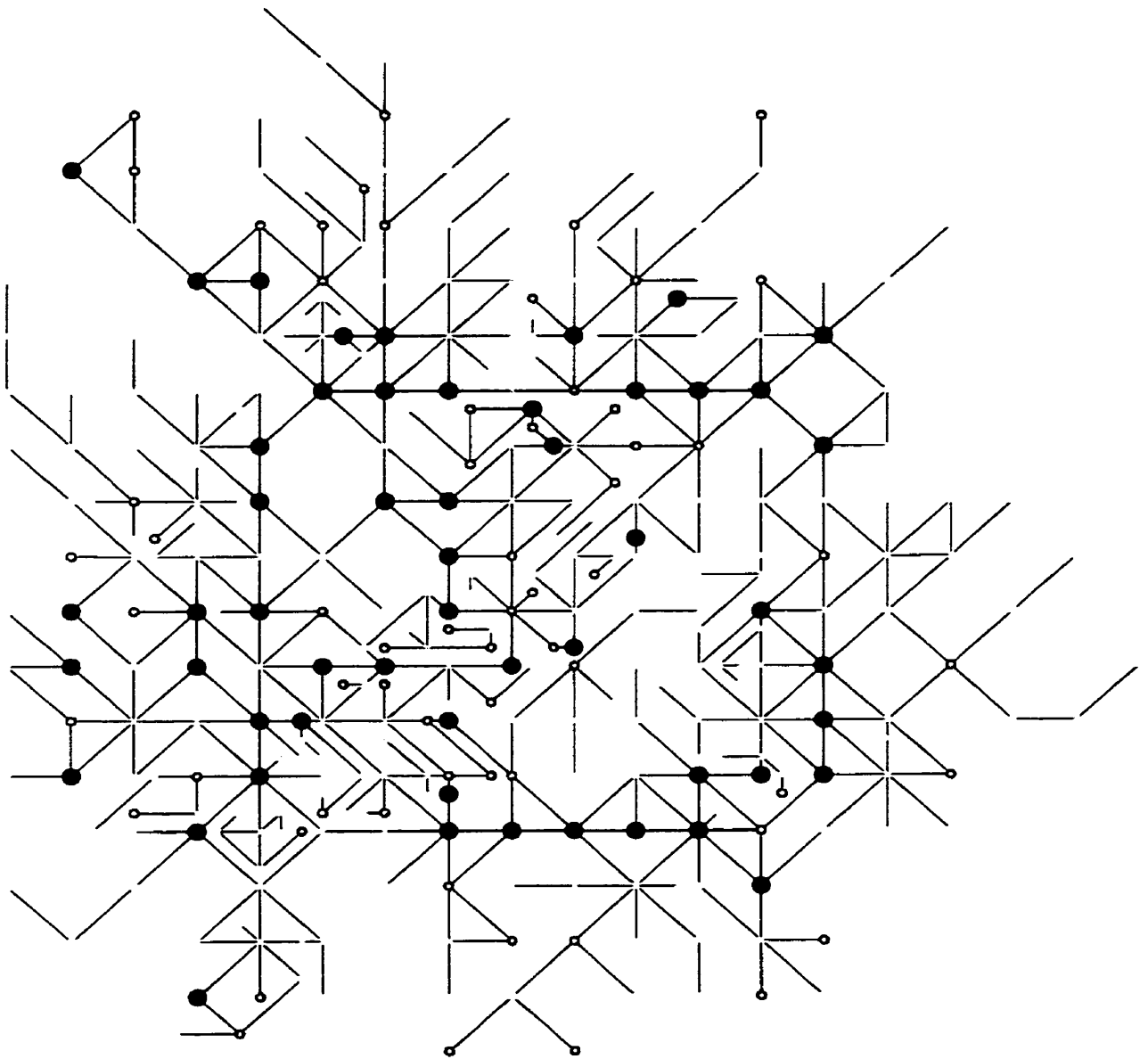


Figure A.9: A 330-bus network with 430 lines - topology layout.

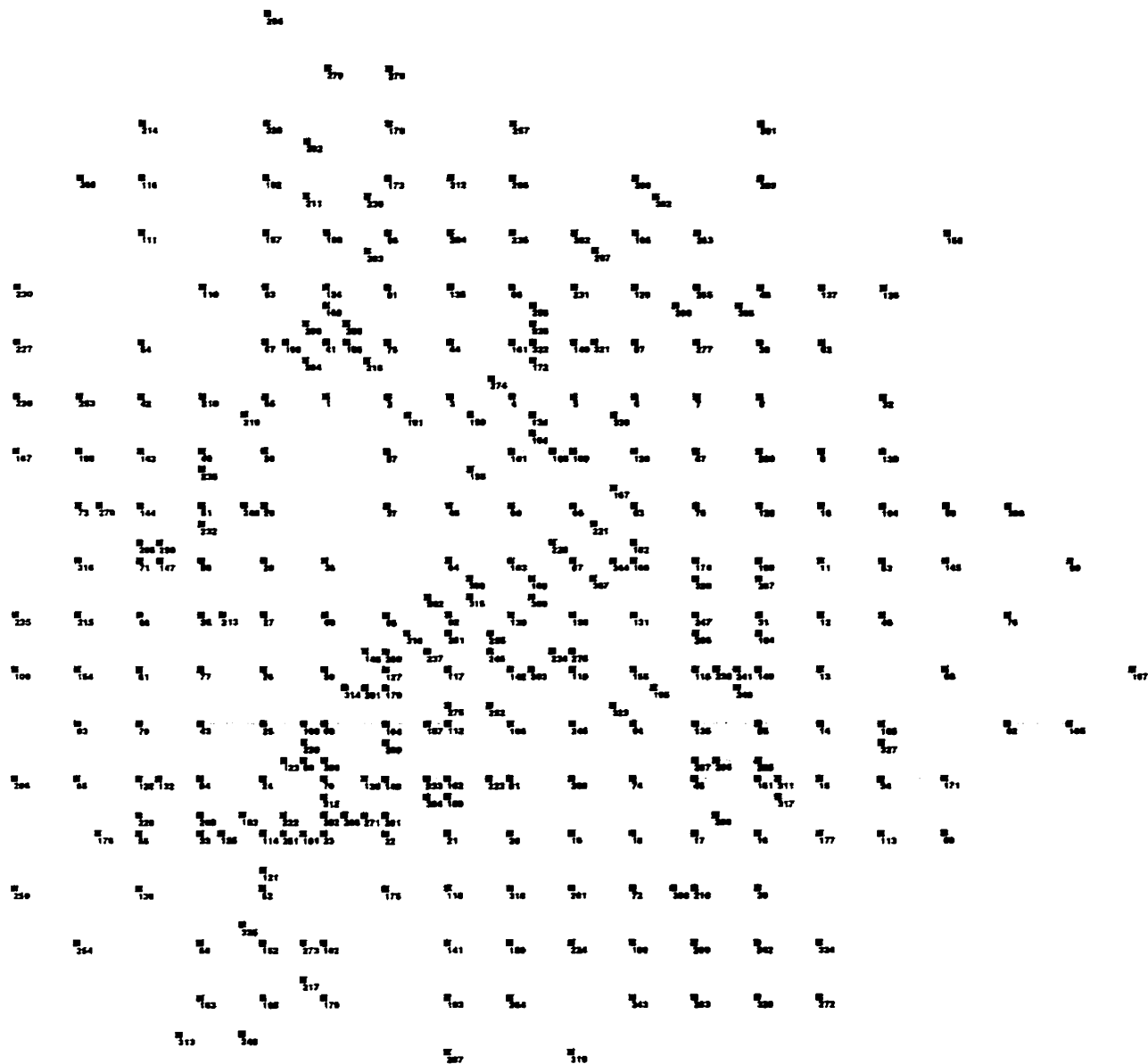


Figure A.10: A 330 bus network with 430 lines - bus numbering.

Line Data

Table A.16: Line data for network of 330 buses and 430 lines.

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the Line (km)
				R (Ω)	X (Ω)	B (mS)			
1	1 - 2	735	5	0.1200	3.3522	1.0969	0.00	23.74	48
2	2 - 3	735	3	0.0833	2.3280	0.2742	0.00	14.24	20
3	3 - 4	735	8	0.1672	4.6705	3.9123	0.00	37.98	107
4	4 - 5	735	6	0.1438	4.0157	1.8921	0.00	28.49	69
5	5 - 6	735	3	0.1667	4.6559	0.5484	0.00	14.24	40
6	6 - 7	735	3	0.2000	5.5871	0.6581	0.00	14.24	48
7	7 - 8	735	7	0.3579	10.1126	13.4184	0.00	33.24	205
8	8 - 9	735	6	0.2125	5.9363	2.7971	0.00	28.49	102
9	9 - 10	735	4	0.1906	5.3252	1.1152	0.00	18.99	61
10	10 - 11	735	5	0.1550	4.3300	1.4168	0.00	23.74	62
11	11 - 12	735	6	0.1604	4.4813	2.1115	0.00	28.49	77
12	12 - 13	735	3	0.0083	0.2328	0.0274	0.00	14.24	2
13	13 - 14	735	4	0.1281	3.5792	0.7495	0.00	18.99	41
14	14 - 15	735	3	0.0333	0.9312	0.1097	0.00	14.24	8
15	15 - 16	735	4	0.1656	4.6268	0.9689	0.00	18.99	53
16	16 - 17	735	10	0.1812	5.0633	6.6271	0.00	47.48	145
17	17 - 18	735	2	0.2187	6.1109	0.3199	0.00	9.50	35
18	18 - 19	735	2	0.5000	13.9677	0.7313	0.00	9.50	80
19	19 - 20	735	4	0.2750	7.6822	1.6088	0.00	18.99	88
20	20 - 21	735	5	0.4050	11.3138	3.7020	0.00	23.74	162

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
21	21 - 22	735	2	0.1312	3.6665	0.1920	0.00	9.50	21
22	22 - 23	735	2	0.2125	5.9363	0.3108	0.00	9.50	34
23	23 - 24	735	2	0.2562	7.1584	0.3748	0.00	9.50	41
24	24 - 25	735	2	0.3125	8.7298	0.4570	0.00	9.50	50
25	25 - 26	735	8	0.2328	6.5037	5.4479	0.00	37.98	149
26	26 - 27	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
27	27 - 28	735	2	0.1875	5.2379	0.2742	0.00	9.50	30
28	28 - 29	735	8	0.2578	7.2021	6.0329	0.00	37.98	165
29	29 - 30	735	4	0.1750	4.8887	1.0238	0.00	18.99	56
30	30 - 1	735	4	0.2312	6.4601	1.3528	0.00	18.99	74
31	13 - 31	735	2	0.6250	17.4596	0.9141	0.00	9.50	100
32	9 - 32	500	2	0.6976	14.4946	0.6261	375.00	5.60	75
33	24 - 33	735	2	0.0687	1.9206	0.1005	0.00	9.50	11
34	14 - 34	500	2	0.9673	20.0991	0.8682	375.00	5.60	104
35	26 - 35	735	2	0.6812	19.0310	0.9963	0.00	9.50	109
36	27 - 36	735	2	0.9312	26.0148	1.3620	0.00	9.50	149
37	29 - 36	735	2	0.6250	17.4596	0.9141	0.00	9.50	100
38	12 - 31	735	2	0.1687	4.7141	0.2468	0.00	9.50	27
39	36 - 37	735	2	0.4125	11.5234	0.6033	0.00	9.50	66
40	7 - 38	735	2	0.8062	22.5229	1.1792	0.00	9.50	129
41	17 - 39	735	2	0.2875	8.0314	0.4205	0.00	9.50	46
42	31 - 11	735	2	0.1062	2.9681	0.1554	0.00	9.50	17

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
43	29 - 40	735	2	1.1562	32.3003	1.6910	0.00	9.50	185
44	40 - 42	735	2	0.7750	21.6499	1.1335	0.00	9.50	124
45	8 - 38	735	2	0.5500	15.3645	0.8044	0.00	9.50	88
46	24 - 43	735	2	0.3375	9.4282	0.4936	0.00	9.50	54
47	2 - 44	735	2	0.4375	12.2217	0.6399	0.00	9.50	70
48	17 - 45	735	2	0.4250	11.8725	0.6216	0.00	9.50	68
49	3 - 44	735	2	0.1500	4.1903	0.2194	0.00	9.50	24
50	37 - 46	735	2	0.3938	10.9996	0.5759	0.00	9.50	63
51	8 - 47	500	2	0.6232	12.9485	0.5593	375.00	5.60	67
52	38 - 48	735	2	1.4812	41.3793	2.1664	0.00	9.50	237
53	7 - 47	500	5	0.1786	3.7106	1.0018	41.67	14.00	48
54	13 - 49	735	2	0.6625	18.5072	0.9689	0.00	9.50	106
55	28 - 50	735	2	0.6875	19.2056	1.0055	0.00	9.50	110
56	28 - 51	735	2	0.6125	17.1104	0.8958	0.00	9.50	98
57	30 - 40	735	2	1.7562	49.0616	2.5686	0.00	9.50	281
58	23 - 52	735	2	0.5500	15.3645	0.8044	0.00	9.50	88
59	12 - 53	500	2	0.6139	12.7552	0.5510	375.00	5.60	66
60	42 - 54	735	2	0.5750	16.0629	0.8410	0.00	9.50	92
61	10 - 53	500	4	0.0372	0.7730	0.1336	46.88	11.20	8
62	33 - 55	735	2	0.6062	16.9358	0.8867	0.00	9.50	97
63	35 - 56	500	2	0.3441	7.1507	0.3089	375.00	5.60	37
64	2 - 57	735	3	0.8750	24.4435	2.8794	0.00	14.24	210

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
65	49 - 53	500	2	0.2976	6.1843	0.2671	75.00	5.60	32
66	52 - 58	735	2	1.0625	29.6814	1.5539	0.00	9.50	170
67	26 - 59	735	2	0.5625	15.7137	0.8227	0.00	9.50	90
68	46 - 60	500	2	0.9766	20.2924	0.8766	375.00	5.60	105
69	46 - 57	735	2	0.9875	27.5862	1.4442	0.00	9.50	158
70	35 - 61	735	2	0.3375	9.4282	0.4936	0.00	9.50	54
71	8 - 62	735	2	1.1375	31.7765	1.6636	0.00	9.50	182
72	47 - 63	500	3	0.9177	19.0684	1.8533	0.00	8.40	148
73	33 - 52	735	2	0.2375	6.6347	0.3474	0.00	9.50	38
74	37 - 64	500	2	0.4837	10.0496	0.4341	375.00	5.60	52
75	30 - 65	735	2	0.8500	23.7451	1.2432	0.00	9.50	136
76	60 - 66	345	2	4.7930	50.4389	1.4360	179.00	2.90	212
77	45 - 16	735	2	0.4625	12.9201	0.6764	0.00	9.50	74
78	1 - 67	735	2	0.9938	27.7608	1.4534	0.00	9.50	159
79	49 - 68	500	2	0.4093	8.5035	0.3673	375.00	5.60	44
80	26 - 69	735	2	1.2250	34.2209	1.7916	0.00	9.50	196
81	1 - 41	735	2	0.4375	12.2217	0.6399	0.00	9.50	70
82	24 - 70	735	3	0.4792	13.3857	1.5768	0.00	14.24	115
83	35 - 71	500	2	0.6325	13.1417	0.5677	375.00	5.60	68
84	17 - 72	735	3	0.6708	18.7400	2.2075	0.00	14.24	161
85	64 - 60	500	2	1.3208	27.4430	1.1855	0.00	5.60	142
86	71 - 73	345	2	1.0174	10.7064	0.3048	179.00	2.90	45

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
87	17 - 74	735	2	0.0687	1.9206	0.1005	0.00	9.50	11
88	2 - 75	735	2	0.1438	4.0157	0.2102	0.00	9.50	23
89	38 - 62	735	2	0.6312	17.6342	0.9232	0.00	9.50	101
90	68 - 76	345	2	1.4696	15.4648	0.4403	179.00	2.90	65
91	25 - 77	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
92	47 - 78	500	2	0.5860	12.1754	0.5259	0.00	5.60	63
93	6 - 47	500	2	2.5485	52.9535	2.2875	187.50	5.60	274
94	43 - 79	500	2	0.8464	17.5867	0.7597	375.00	5.60	91
95	26 - 80	500	2	0.4372	9.0833	0.3924	375.00	5.60	47
96	20 - 81	500	2	0.1953	4.0585	0.1753	375.00	5.60	21
97	25 - 43	735	2	0.7625	21.3007	1.1152	0.00	9.50	122
98	68 - 82	345	2	2.2835	24.0298	0.6841	179.00	2.90	101
99	67 - 83	500	2	0.1860	3.8652	0.1670	375.00	5.60	20
100	24 - 84	735	4	0.8969	25.0546	5.2468	0.00	18.99	287
101	62 - 32	500	2	0.7720	16.0407	0.6929	187.50	5.60	83
102	14 - 85	735	2	1.5000	41.9031	2.1938	0.00	9.50	240
103	44 - 86	735	2	0.1562	4.3649	0.2285	0.00	9.50	25
104	63 - 87	500	2	0.9487	19.7126	0.8515	0.00	5.60	102
105	19 - 81	500	8	0.0512	1.0629	0.7347	22.06	22.40	22
106	36 - 88	735	2	1.7250	48.1886	2.5229	0.00	9.50	276
107	34 - 89	345	2	1.3339	14.0372	0.3996	179.00	2.90	59
108	25 - 90	735	2	0.5812	16.2375	0.8501	0.00	9.50	93

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
109	1 - 57	735	2	0.3812	10.6504	0.5576	0.00	9.50	61
110	75 - 91	735	2	0.2187	6.1109	0.3199	0.00	9.50	35
111	64 - 92	500	2	2.6695	55.4659	2.3960	0.00	5.60	287
112	79 - 93	345	2	0.2713	2.8550	0.0813	179.00	2.90	12
113	13 - 85	735	2	0.3562	9.9520	0.5210	0.00	9.50	57
114	45 - 94	735	2	1.1688	32.6495	1.7093	0.00	9.50	187
115	79 - 95	345	2	2.2383	23.5540	0.6706	179.00	2.90	99
116	91 - 96	500	2	0.0651	1.3528	0.0584	375.00	5.60	7
117	59 - 69	735	2	0.3125	8.7298	0.4570	0.00	9.50	50
118	7 - 97	735	2	0.8688	24.2689	1.2706	0.00	9.50	139
119	53 - 98	500	2	1.4453	17.0470	1.0149	0.00	5.77	104
120	76 - 99	345	2	1.0174	10.7064	0.3048	0.00	2.90	45
121	19 - 74	735	2	0.7562	21.1261	1.1060	0.00	9.50	121
122	25 - 100	735	2	0.8188	22.8721	1.1974	0.00	9.50	131
123	46 - 101	735	2	0.2250	6.2855	0.3291	0.00	9.50	36
124	52 - 102	735	4	0.5125	14.3169	2.9982	0.00	18.99	164
125	27 - 80	500	7	0.0771	1.6013	0.8474	26.79	19.60	29
126	60 - 103	500	2	0.7999	16.6204	0.7180	0.00	5.60	86
127	69 - 104	735	4	0.5406	15.1026	3.1627	0.00	18.99	173
128	14 - 105	735	3	0.9875	27.5862	3.2496	0.00	14.24	237
129	19 - 72	735	2	0.3250	9.0790	0.4753	0.00	9.50	52
130	81 - 106	500	3	0.3224	6.6997	0.6512	0.00	8.40	52

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
131	73 - 107	345	2	1.4922	15.7027	0.4470	0.00	2.90	66
132	60 - 108	500	2	1.3673	28.4093	1.2272	0.00	5.60	147
133	100 - 69	735	2	0.4687	13.0947	0.6856	0.00	9.50	75
134	93 - 109	345	2	1.0852	11.4201	0.3251	0.00	2.90	48
135	67 - 110	735	2	0.4562	12.7455	0.6673	0.00	9.50	73
136	110 - 111	735	2	0.9250	25.8402	1.3528	0.00	9.50	148
137	101 - 60	500	2	1.3022	27.0565	1.1688	125.00	5.60	140
138	81 - 112	500	2	1.0975	22.8048	0.9851	0.00	5.60	118
139	34 - 113	345	2	0.6104	6.4238	0.1829	179.00	2.90	27
140	24 - 114	735	2	0.7062	19.7294	1.0329	0.00	9.50	113
141	77 - 79	500	3	0.4279	8.8900	0.8641	75.00	8.40	69
142	85 - 115	735	2	0.6375	17.8088	0.9324	0.00	9.50	102
143	111 - 116	500	2	0.4558	9.4698	0.4091	375.00	5.60	49
144	104 - 117	735	2	0.6062	16.9358	0.8867	0.00	9.50	97
145	62 - 48	735	2	0.2187	6.1109	0.3199	0.00	9.50	35
146	21 - 118	500	2	0.5953	12.3687	0.5343	375.00	5.60	64
147	106 - 119	500	5	0.4985	10.3588	2.7967	0.00	14.00	134
148	108 - 120	345	2	1.0626	11.1822	0.3183	179.00	2.90	47
149	20 - 118	500	6	0.4837	10.0496	3.9070	93.75	16.80	156
150	114 - 121	500	2	0.1209	2.5124	0.1085	375.00	5.60	13
151	43 - 122	735	2	0.9500	26.5386	1.3894	0.00	9.50	152
152	24 - 123	735	4	0.2219	6.1982	1.2980	0.00	18.99	71

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
153	64 - 103	500	2	0.9115	18.9396	0.8181	0.00	5.60	98
154	75 - 124	500	2	0.5023	10.4361	0.4508	375.00	5.60	54
155	114 - 125	735	2	1.2250	34.2209	1.7916	0.00	9.50	196
156	62 - 126	500	2	0.1023	2.1259	0.0918	375.00	5.60	11
157	75 - 44	735	2	0.0562	1.5714	0.0823	0.00	9.50	9
158	59 - 127	735	2	0.9375	26.1894	1.3711	0.00	9.50	150
159	9 - 128	500	2	0.2697	5.6046	0.2421	375.00	5.60	29
160	97 - 129	500	2	0.1395	2.8989	0.1252	375.00	5.60	15
161	39 - 16	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
162	92 - 130	345	2	0.7461	7.8513	0.2235	89.50	2.90	33
163	119 - 131	500	5	0.5544	11.5183	3.1098	0.00	14.00	149
164	84 - 132	735	2	0.1000	2.7935	0.1463	0.00	9.50	16
165	13 - 105	735	2	0.5062	14.1423	0.7404	0.00	9.50	81
166	100 - 133	735	2	1.8437	51.5059	2.6965	0.00	9.50	295
167	108 - 134	500	2	1.6277	33.8207	1.4610	0.00	5.60	175
168	85 - 135	735	2	0.9125	25.4911	1.3346	0.00	9.50	146
169	103 - 66	345	2	1.0337	12.6750	0.5882	59.67	4.19	68
170	44 - 136	735	2	1.0438	29.1576	1.5265	0.00	9.50	167
171	62 - 137	735	3	0.5667	15.8301	1.8647	0.00	14.24	136
172	9 - 138	735	2	0.5688	15.8883	0.8318	0.00	9.50	91
173	105 - 68	500	2	2.6961	31.7991	1.8931	187.50	5.77	194
174	33 - 139	735	2	1.9312	53.9502	2.8245	0.00	9.50	309

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
175	5 - 140	500	2	0.2883	5.9911	0.2588	375.00	5.60	31
176	118 - 141	500	3	0.7069	14.6878	1.4276	0.00	8.40	114
177	95 - 93	345	2	1.6722	20.5037	0.9516	0.00	4.19	110
178	117 - 142	735	2	0.3938	10.9996	0.5759	0.00	9.50	63
179	51 - 143	735	2	0.7938	22.1737	1.1609	0.00	9.50	127
180	51 - 144	500	2	0.0837	1.7393	0.0751	375.00	5.60	9
181	61 - 79	500	2	1.1534	23.9643	1.0352	187.50	5.60	124
182	53 - 145	345	2	1.3339	14.0372	0.3996	179.00	2.90	59
183	80 - 146	500	2	0.1581	3.2854	0.1419	0.00	5.60	17
184	50 - 147	735	2	0.4312	12.0471	0.6307	0.00	9.50	69
185	18 - 74	735	2	1.3437	37.5382	1.9653	0.00	9.50	215
186	69 - 148	735	5	0.4725	13.1995	4.3190	0.00	23.74	189
187	85 - 149	735	2	0.4500	12.5709	0.6581	0.00	9.50	72
188	134 - 150	345	2	0.2487	2.6171	0.0745	179.00	2.90	11
189	75 - 136	735	2	0.4938	13.7931	0.7221	0.00	9.50	79
190	45 - 151	500	2	1.1441	23.7711	1.0268	375.00	5.60	123
191	52 - 152	735	2	1.4125	39.4588	2.0658	0.00	9.50	226
192	150 - 153	345	2	4.1374	43.5392	1.2395	0.00	2.90	183
193	31 - 115	735	2	1.3625	38.0620	1.9927	0.00	9.50	218
194	79 - 154	500	2	2.2044	45.8028	1.9786	0.00	5.60	237
195	94 - 155	735	2	1.0875	30.3798	1.5905	0.00	9.50	174
196	130 - 156	345	2	2.5083	30.7556	1.4274	0.00	4.19	165

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
197	127 - 146	500	4	0.7953	16.5238	2.8551	125.00	11.20	171
198	124 - 157	345	2	0.6330	6.6617	0.1897	179.00	2.90	28
199	126 - 158	345	2	0.6783	7.1376	0.2032	179.00	2.90	30
200	118 - 159	345	2	2.2383	23.5540	0.6706	179.00	2.90	99
201	74 - 45	735	2	0.1188	3.3173	0.1737	0.00	9.50	19
202	156 - 160	345	2	3.1924	39.1435	1.8166	0.00	4.19	210
203	44 - 161	735	4	0.2688	7.5076	1.5722	0.00	18.99	86
204	104 - 162	735	2	0.8800	24.5832	1.2870	0.00	9.50	141
205	15 - 85	735	2	1.3437	37.5382	1.9653	0.00	9.50	215
206	152 - 163	735	2	0.9125	25.4911	1.3346	0.00	9.50	146
207	134 - 164	345	2	3.9791	41.8738	1.1921	179.00	2.90	176
208	82 - 165	345	2	0.6783	7.1376	0.2032	0.00	2.90	30
209	15 - 34	500	2	0.7906	16.4272	0.7096	93.75	5.60	85
210	101 - 166	500	2	0.6418	13.3350	0.5760	375.00	5.60	69
211	108 - 167	345	2	0.4522	4.7584	0.1355	179.00	2.90	20
212	41 - 168	735	7	0.2893	8.0813	5.1828	0.00	33.24	162
213	5 - 97	735	2	0.9188	25.6657	1.3437	0.00	9.50	147
214	156 - 169	345	2	3.2104	33.7845	0.9618	0.00	2.90	142
215	102 - 170	735	2	0.3938	10.9996	0.5759	0.00	9.50	63
216	34 - 171	345	2	2.5096	26.4090	0.7518	179.00	2.90	111
217	140 - 129	500	3	0.8867	18.4242	1.7907	0.00	8.40	143
218	5 - 172	735	2	0.6938	19.3802	1.0146	0.00	9.50	111

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
219	96 - 173	500	2	1.3115	27.2498	1.1771	0.00	5.60	141
220	63 - 174	345	2	1.9217	20.2231	0.5757	179.00	2.90	85
221	13 - 149	735	2	1.0125	28.2846	1.4808	0.00	9.50	162
222	21 - 175	735	2	0.9312	26.0148	1.3620	0.00	9.50	149
223	132 - 176	735	2	0.4938	13.7931	0.7221	0.00	9.50	79
224	34 - 177	500	2	0.8371	17.3935	0.7514	0.00	5.60	90
225	83 - 157	345	2	0.8817	10.8111	0.5017	59.67	4.19	58
226	173 - 178	345	2	1.1757	12.3718	0.3522	179.00	2.90	52
227	104 - 179	500	2	0.1488	3.0922	0.1336	375.00	5.60	16
228	72 - 180	735	3	1.4125	39.4588	4.6481	0.00	14.24	339
229	142 - 130	345	11	0.0553	0.6778	0.9516	8.52	23.03	20
230	121 - 181	345	2	0.1357	1.4275	0.0406	179.00	2.90	6
231	63 - 182	345	2	4.0470	42.5875	1.2124	179.00	2.90	179
232	125 - 183	735	2	0.3375	9.4282	0.4936	0.00	9.50	54
233	105 - 171	345	5	0.1520	1.8640	0.5407	19.89	10.47	25
234	149 - 184	735	2	0.1625	4.5395	0.2377	0.00	9.50	26
235	129 - 185	500	10	0.3907	8.1170	8.7658	0.00	28.00	210
236	75 - 186	735	2	0.7125	19.9040	1.0421	0.00	9.50	114
237	67 - 124	500	3	1.2526	26.0258	2.5296	125.00	8.40	202
238	104 - 187	500	2	0.7162	14.8811	0.6428	375.00	5.60	77
239	124 - 188	345	2	1.2661	13.3235	0.3793	179.00	2.90	56
240	21 - 189	735	2	0.8812	24.6181	1.2889	0.00	9.50	141

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
241	35 - 50	735	2	1.2625	35.2684	1.8464	0.00	9.50	202
242	41 - 190	735	4	0.5062	14.1423	2.9616	0.00	18.99	162
243	153 - 191	345	2	0.8139	8.5651	0.2438	0.00	2.90	36
244	188 - 192	345	2	1.5374	16.1785	0.4606	0.00	2.90	68
245	138 - 32	500	2	1.6260	19.1778	1.1417	125.00	5.77	117
246	141 - 193	500	2	2.8073	33.1104	1.9712	0.00	5.77	202
247	53 - 194	345	2	1.7635	18.5577	0.5283	179.00	2.90	78
248	135 - 195	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
249	31 - 184	735	2	1.3688	38.2366	2.0018	0.00	9.50	219
250	152 - 196	500	2	0.4372	9.0833	0.3924	375.00	5.60	47
251	165 - 197	345	2	1.2209	12.8476	0.3658	0.00	2.90	54
252	144 - 198	345	2	4.5896	48.2976	1.3750	179.00	2.90	203
253	86 - 136	735	2	1.2250	34.2209	1.7916	0.00	9.50	196
254	128 - 199	345	2	2.3739	24.9815	0.7112	179.00	2.90	105
255	168 - 200	735	2	0.3500	9.7774	0.5119	0.00	9.50	56
256	148 - 201	735	3	1.4500	40.5063	4.7715	0.00	14.24	348
257	186 - 41	735	2	0.2937	8.2060	0.4296	0.00	9.50	47
258	146 - 202	500	4	0.5860	12.1754	2.1038	0.00	11.20	126
259	124 - 203	500	2	1.8509	38.4589	1.6613	0.00	5.60	199
260	41 - 204	735	5	0.4775	13.3392	4.3647	0.00	23.74	191
261	27 - 50	735	2	1.5187	42.4269	2.2212	0.00	9.50	243
262	144 - 205	345	2	4.5670	48.0597	1.3682	179.00	2.90	202

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
263	148 - 206	735	2	0.6437	17.9834	0.9415	0.00	9.50	103
264	135 - 207	500	2	0.4465	9.2765	0.4007	375.00	5.60	48
265	78 - 174	345	2	1.4442	17.7078	0.8218	89.50	4.19	95
266	168 - 208	735	2	0.2750	7.6822	0.4022	0.00	9.50	44
267	84 - 209	735	2	0.5700	15.9232	0.8336	0.00	9.50	91
268	40 - 210	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
269	166 - 108	500	2	0.9394	19.5193	0.8432	0.00	5.60	101
270	203 - 211	345	2	4.6800	49.2493	1.4021	179.00	2.90	207
271	96 - 212	345	2	1.5148	15.9406	0.4538	179.00	2.90	67
272	27 - 213	735	2	0.6250	17.4596	0.9141	0.00	9.50	100
273	92 - 202	500	2	0.9394	19.5193	0.8432	0.00	5.60	101
274	116 - 214	345	2	0.1809	1.9034	0.0542	179.00	2.90	8
275	61 - 215	500	2	0.2139	4.4450	0.1920	375.00	5.60	23
276	186 - 216	735	2	0.5688	15.8883	0.8318	0.00	9.50	91
277	154 - 109	345	4	0.1140	1.3980	0.2595	25.57	8.38	15
278	152 - 217	735	2	0.3188	8.9044	0.4662	0.00	9.50	51
279	17 - 218	735	3	0.5167	14.4333	1.7002	0.00	14.24	124
280	40 - 219	500	2	0.9208	19.1328	0.8265	375.00	5.60	99
281	37 - 57	735	2	0.6125	17.1104	0.8958	0.00	9.50	98
282	198 - 220	345	2	2.1885	23.0306	0.6557	0.00	2.90	97
283	169 - 221	345	2	1.9896	20.9369	0.5961	0.00	2.90	88
284	114 - 222	500	2	0.3348	6.9574	0.3005	375.00	5.60	36

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
285	47 - 120	345	2	3.0556	37.4659	1.7388	89.50	4.19	201
286	187 - 223	345	2	2.9843	31.4053	0.8941	179.00	2.90	132
287	72 - 224	735	3	1.2792	35.7340	4.2093	0.00	14.24	307
288	154 - 225	500	2	1.6184	33.6274	1.4526	0.00	5.60	174
289	87 - 156	345	2	1.1249	13.7934	0.6401	89.50	4.19	74
290	167 - 226	345	2	1.5826	16.6543	0.4741	0.00	2.90	70
291	220 - 227	345	2	0.9948	10.4684	0.2980	0.00	2.90	44
292	209 - 228	500	2	0.4186	8.6967	0.3757	375.00	5.60	45
293	127 - 117	735	3	0.4292	11.9889	1.4123	0.00	14.24	103
294	100 - 229	735	2	1.1188	31.2527	1.6362	0.00	9.50	179
295	227 - 230	345	2	0.7009	7.3755	0.2100	0.00	2.90	31
296	140 - 231	500	2	1.4510	30.1487	1.3023	0.00	5.60	156
297	125 - 121	500	4	0.0512	1.0629	0.1837	46.88	11.20	11
298	147 - 232	735	2	0.6062	16.9358	0.8867	0.00	9.50	97
299	148 - 233	500	2	1.0975	22.8048	0.9851	375.00	5.60	118
300	130 - 234	345	7	1.5245	18.6930	10.6273	0.00	14.66	351
301	110 - 157	345	5	0.4074	4.9955	1.4490	29.83	10.47	67
302	136 - 235	735	2	1.9312	53.9502	2.8245	0.00	9.50	309
303	51 - 236	500	2	1.0882	22.6115	0.9768	375.00	5.60	117
304	202 - 237	500	5	0.8334	17.3162	4.6751	0.00	14.00	224
305	189 - 162	735	3	0.3583	10.0102	1.1792	0.00	14.24	86
306	184 - 238	735	2	1.4750	41.2047	2.1572	0.00	9.50	236

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
307	203 - 239	345	2	2.2157	23.3161	0.6638	179.00	2.90	98
308	51 - 240	500	2	0.2232	4.6383	0.2004	375.00	5.60	24
309	110 - 83	500	3	0.6945	14.4301	1.4025	93.75	8.40	112
310	238 - 241	500	2	0.4744	9.8563	0.4258	375.00	5.60	51
311	218 - 242	735	2	0.9562	26.7132	1.3985	0.00	9.50	153
312	224 - 243	735	3	0.4792	13.3857	1.5768	0.00	14.24	115
313	65 - 219	500	3	0.6325	13.1417	1.2773	93.75	8.40	102
314	87 - 244	500	2	2.0556	42.7107	1.8450	0.00	5.60	221
315	119 - 245	345	2	3.6174	38.0671	1.0837	179.00	2.90	160
316	237 - 246	500	2	0.9301	19.3261	0.8348	0.00	5.60	100
317	58 - 152	735	2	0.9938	27.7608	1.4534	0.00	9.50	159
318	131 - 247	500	2	0.5420	6.3926	0.3806	0.00	5.77	39
319	217 - 248	500	2	0.4279	8.8900	0.3840	375.00	5.60	46
320	238 - 249	735	2	0.2125	5.9363	0.3108	0.00	9.50	34
321	103 - 130	345	3	1.4290	17.5214	1.8296	59.67	6.28	141
322	51 - 250	500	2	0.0558	1.1596	0.0501	375.00	5.60	6
323	222 - 251	345	2	2.2609	23.7919	0.6773	179.00	2.90	100
324	117 - 252	735	2	0.2250	6.2855	0.3291	0.00	9.50	36
325	39 - 242	735	2	1.0500	29.3322	1.5357	0.00	9.50	168
326	198 - 253	345	2	0.7009	7.3755	0.2100	0.00	2.90	31
327	139 - 254	735	2	0.0188	0.5238	0.0274	0.00	9.50	3
328	246 - 255	500	2	0.7720	16.0407	0.6929	0.00	5.60	83

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
329	21 - 148	735	2	1.0812	30.2052	1.5814	0.00	9.50	173
330	140 - 256	345	2	2.3965	25.2194	0.7180	179.00	2.90	106
331	212 - 257	345	2	2.2970	24.1726	0.6882	0.00	2.90	102
332	237 - 258	345	2	0.0904	0.9517	0.0271	179.00	2.90	4
333	6 - 97	735	2	0.7500	20.9516	1.0969	0.00	9.50	120
334	254 - 259	735	2	0.8688	24.2689	1.2706	0.00	9.50	139
335	245 - 260	345	2	0.4296	4.5205	0.1287	0.00	2.90	19
336	255 - 261	345	2	0.7009	7.3755	0.2100	179.00	2.90	31
337	166 - 164	345	4	0.7829	9.5995	1.7820	44.75	8.38	103
338	231 - 262	345	2	1.4470	15.2268	0.4335	179.00	2.90	64
339	129 - 263	500	2	2.1680	25.5704	1.5223	0.00	5.77	156
340	224 - 264	735	2	0.3062	8.5552	0.4479	0.00	9.50	49
341	75 - 216	735	2	0.7938	22.1737	1.1609	0.00	9.50	127
342	129 - 265	345	2	0.3391	3.5688	0.1016	179.00	2.90	15
343	115 - 266	735	2	0.4562	12.7455	0.6673	0.00	9.50	73
344	266 - 267	735	2	0.0438	1.2222	0.0640	0.00	9.50	7
345	11 - 128	500	2	1.0882	22.6115	0.9768	125.00	5.60	117
346	111 - 268	500	2	0.1209	2.5124	0.1085	375.00	5.60	13
347	72 - 269	735	2	0.3188	8.9044	0.4662	0.00	9.50	51
348	144 - 270	345	2	1.8765	19.7473	0.5622	179.00	2.90	83
349	182 - 160	345	2	0.2888	3.5416	0.1644	0.00	4.19	19
350	201 - 271	735	2	0.5875	16.4120	0.8592	0.00	9.50	94

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
351	242 - 272	735	2	1.1812	32.9987	1.7276	0.00	9.50	189
352	152 - 273	735	2	0.5562	15.5391	0.8135	0.00	9.50	89
353	49 - 145	345	2	1.1249	13.7934	0.6401	59.67	4.19	74
354	44 - 274	735	2	1.2562	35.0939	1.8373	0.00	9.50	201
355	117 - 275	735	2	0.5312	14.8407	0.7770	0.00	9.50	85
356	156 - 276	345	2	3.7757	39.7325	1.1312	0.00	2.90	167
357	134 - 153	345	3	0.6892	8.4500	0.8824	44.75	6.28	68
358	97 - 277	735	2	0.8188	22.8721	1.1974	0.00	9.50	131
359	178 - 278	345	2	0.6783	7.1376	0.2032	0.00	2.90	30
360	178 - 279	345	2	0.2487	2.6171	0.0745	0.00	2.90	11
361	276 - 234	345	2	0.6233	7.6423	0.3547	0.00	4.19	41
362	128 - 280	500	2	1.5626	32.4678	1.4025	0.00	5.60	168
363	72 - 281	735	3	0.7000	19.5548	2.3035	0.00	14.24	168
364	133 - 282	735	2	0.8938	24.9673	1.3071	0.00	9.50	143
365	112 - 187	500	2	2.8090	58.3648	2.5212	0.00	5.60	302
366	269 - 283	500	2	0.6418	13.3350	0.5760	375.00	5.60	69
367	136 - 284	735	2	0.5812	16.2375	0.8501	0.00	9.50	93
368	85 - 285	500	2	1.0510	21.8385	0.9434	375.00	5.60	113
369	141 - 159	345	2	0.3952	4.8463	0.2249	89.50	4.19	26
370	95 - 286	345	2	2.1026	22.1265	0.6299	0.00	2.90	93
371	264 - 287	500	2	0.4093	8.5035	0.3673	375.00	5.60	44
372	97 - 288	735	2	0.2625	7.3330	0.3839	0.00	9.50	42

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
373	215 - 71	500	2	1.2371	25.7037	1.1103	0.00	5.60	133
374	229 - 289	735	2	0.7375	20.6024	1.0786	0.00	9.50	118
375	233 - 290	345	2	2.7130	28.5503	0.8128	179.00	2.90	120
376	69 - 291	735	2	0.4687	13.0947	0.6856	0.00	9.50	75
377	1 - 216	735	2	0.2437	6.8093	0.3565	0.00	9.50	39
378	239 - 292	345	2	1.6957	17.8439	0.5080	0.00	2.90	75
379	263 - 293	500	2	1.7765	36.9128	1.5945	0.00	5.60	191
380	279 - 294	345	2	1.2887	13.5614	0.3861	0.00	2.90	57
381	267 - 199	345	2	3.2532	39.8891	1.8512	89.50	4.19	214
382	285 - 295	345	2	1.5826	16.6543	0.4741	179.00	2.90	70
383	284 - 296	735	2	0.2062	5.7617	0.3016	0.00	9.50	33
384	129 - 297	345	2	5.4487	57.3385	1.6324	179.00	2.90	241
385	98 - 145	345	2	0.3800	4.6599	0.2163	89.50	4.19	25
386	17 - 298	735	2	0.7687	21.4753	1.1243	0.00	9.50	123
387	262 - 299	345	2	0.8139	8.5651	0.2438	0.00	2.90	36
388	130 - 300	345	9	0.4088	5.0120	4.7103	0.00	18.85	121
389	77 - 35	735	2	0.7625	21.3007	1.1152	0.00	9.50	122
390	293 - 301	345	2	1.5826	16.6543	0.4741	179.00	2.90	70
391	297 - 302	345	2	2.8939	30.4537	0.8670	0.00	2.90	128
392	252 - 303	735	2	0.0500	1.3968	0.0731	0.00	9.50	8
393	162 - 233	500	3	0.4527	9.4054	0.9141	75.00	8.40	73
394	233 - 304	500	2	0.4279	8.8900	0.3840	0.00	5.60	46

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
395	277 - 305	735	2	0.0312	0.8730	0.0457	0.00	9.50	5
396	145 - 306	345	2	1.4898	18.2670	0.8478	0.00	4.19	98
397	268 - 214	345	2	2.2803	27.9596	1.2976	89.50	4.19	150
398	244 - 307	345	2	0.2939	3.0930	0.0881	179.00	2.90	13
399	72 - 308	735	2	0.7812	21.8245	1.1426	0.00	9.50	125
400	130 - 309	345	10	1.1067	13.5697	15.7442	0.00	20.94	364
401	151 - 285	500	2	1.9068	39.6185	1.7114	0.00	5.60	205
402	237 - 310	500	2	0.6232	12.9485	0.5593	0.00	5.60	67
403	285 - 311	500	2	1.1441	23.7711	1.0268	0.00	5.60	123
404	282 - 312	735	2	1.1437	31.9511	1.6728	0.00	9.50	183
405	162 - 223	345	4	1.0261	12.5818	2.3357	59.67	8.38	135
406	248 - 313	345	2	1.8539	19.5094	0.5554	179.00	2.90	82
407	291 - 314	500	2	0.3907	8.1170	0.3506	375.00	5.60	42
408	300 - 315	345	8	0.5245	6.4307	4.7752	0.00	16.75	138
409	102 - 273	735	2	0.9188	25.6657	1.3437	0.00	9.50	147
410	71 - 316	345	2	1.6957	17.8439	0.5080	179.00	2.90	75
411	311 - 317	345	2	0.2035	2.1413	0.0610	179.00	2.90	9
412	281 - 318	735	3	0.9000	25.1419	2.9616	0.00	14.24	216
413	122 - 79	500	2	1.5426	18.1943	1.0832	125.00	5.77	111
414	264 - 319	500	2	0.5209	10.8226	0.4675	375.00	5.60	56
415	267 - 320	735	2	0.8350	23.3261	1.2212	0.00	9.50	134
416	97 - 321	735	2	0.7687	21.4753	1.1243	0.00	9.50	123

Table A.16: Line data for network of 330 buses and 430 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
417	39 - 177	500	3	1.1099	23.0625	2.2415	125.00	8.40	179
418	140 - 322	500	2	1.8509	38.4589	1.6613	0.00	5.60	199
419	119 - 323	345	2	1.4470	15.2268	0.4335	179.00	2.90	64
420	242 - 324	500	2	0.4837	10.0496	0.4341	375.00	5.60	52
421	163 - 248	500	4	0.2046	4.2517	0.7347	46.88	11.20	44
422	152 - 325	500	2	0.9952	20.6789	0.8933	375.00	5.60	107
423	322 - 326	500	2	0.6511	13.5283	0.5844	0.00	5.60	70
424	34 - 327	345	2	0.2487	2.6171	0.0745	179.00	2.90	11
425	127 - 291	735	2	0.7187	20.0786	1.0512	0.00	9.50	115
426	192 - 328	345	2	1.2887	13.5614	0.3861	0.00	2.90	57
427	242 - 329	500	2	0.5953	12.3687	0.5343	375.00	5.60	64
428	108 - 330	500	2	4.3638	51.4687	3.0641	0.00	5.77	314
429	288 - 305	735	2	0.7125	19.9040	1.0421	0.00	9.50	114
430	105 - 327	345	2	2.2347	27.4004	1.2716	89.50	4.19	147

Bus Data

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines.

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MW)	Q_{gmin} (MVA _r)	Q_{gmax} (MVA _r)	P_d (MW)	Q_d (MVA _r)
1	1.0000	41990.00	36753.85	0.00	2124.00	6520.00	326.00
2	1.0000	14660.00	14060.50	0.00	2480.00	9208.88	1981.53
3	1.0000	5520.00	5219.65	-15.00	40.00	2800.00	91.73
5	1.0100	0.00	0.00	0.00	1071.00	564.57	1187.23
6	1.0062	2610.00	2603.95	-15.00	40.00	1063.47	297.95
7	1.0000	2970.00	2966.84	-15.00	40.00	705.99	4461.50
8	1.0000	8000.00	7983.68	-15.00	40.00	4960.00	4288.38
9	1.0000	4750.00	4469.93	-15.00	40.00	3440.00	1312.35
11	1.0015	0.00	0.00	0.00	666.00	6355.66	317.78
13	0.9977	5990.00	5986.74	-30.00	50.00	680.14	2294.17
14	1.0000	6720.00	6661.56	-15.00	40.00	3560.00	1236.10
15	1.0000	5670.00	5352.81	-15.00	40.00	898.89	1169.92
16	1.0046	0.00	0.00	0.00	591.00	6437.84	321.89
17	1.0000	23220.00	21183.83	-15.00	40.00	8040.00	1252.37
18	1.0000	6920.00	5841.17	-50.00	82.00	134.64	867.53
19	1.0000	23170.00	22249.40	0.00	564.00	1032.20	51.61
20	1.0059	2210.00	2203.62	-15.00	40.00	1367.19	337.63
21	0.9969	6040.00	6031.08	-15.00	40.00	1404.47	1189.33
24	1.0000	28440.00	27450.42	0.00	3105.00	9200.00	1051.79
25	1.0000	18410.00	16932.91	-15.00	40.00	3689.69	2134.61

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
27	1.0061	3970.00	3967.38	-15.00	40.00	1028.56	1545.26
29	1.0228	2840.00	2835.44	-30.00	50.00	1201.69	777.88
30	1.0154	12690.00	12687.68	-15.00	40.00	336.12	1174.84
31	1.0001	7290.00	7284.10	-30.00	50.00	955.23	1273.87
33	0.9973	6250.00	6246.87	-39.00	65.00	700.96	35.05
35	1.0008	2420.00	2417.27	-15.00	40.00	3680.81	848.03
37	1.0066	4260.00	4251.98	-30.00	50.00	1011.43	343.28
39	0.9928	4950.00	4936.78	-30.00	50.00	1566.58	1463.08
45	0.9989	3710.00	3704.44	-30.00	50.00	1922.69	1238.17
46	1.0049	2760.00	2756.30	-30.00	50.00	790.18	513.95
47	1.0000	0.00	0.00	-50.00	205.00	256.40	12.82
48	1.0081	0.00	0.00	0.00	2781.00	5089.40	254.47
56	1.0000	0.00	0.00	-50.00	281.00	422.72	138.94
59	1.0066	5440.00	5438.20	-30.00	50.00	488.07	348.35
62	0.9776	5050.00	5045.43	-30.00	50.00	669.18	3829.55
64	1.0000	6140.00	6127.94	-15.00	40.00	1404.68	396.33
68	1.0000	0.00	0.00	-39.00	64.00	393.21	305.97
75	0.9933	16530.00	16520.53	0.00	2399.00	740.25	37.01
77	0.9956	3630.00	3622.39	-15.00	40.00	1114.92	773.08
80	1.0000	0.00	0.00	0.00	1098.00	1227.67	61.38
81	1.0000	0.00	0.00	0.00	1197.00	456.43	22.82
83	1.0000	1260.00	1254.81	-50.00	114.00	1920.18	22.85

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
84	1.0000	0.00	0.00	0.00	869.00	336.66	542.38
92	1.0011	2890.00	2884.00	0.00	307.00	1138.69	56.93
93	1.0000	0.00	0.00	-30.00	50.00	684.22	33.28
95	1.0000	1630.00	1622.25	-15.00	40.00	932.26	159.39
96	1.0000	0.00	0.00	0.00	337.00	17.55	325.89
100	0.9783	4570.00	4560.36	-30.00	50.00	205.83	2577.92
103	0.9991	0.00	0.00	-50.00	265.00	1888.45	94.42
110	0.9722	2480.00	2471.98	-30.00	50.00	540.09	583.58
112	0.9936	2670.00	2662.58	-15.00	40.00	1480.49	242.84
116	1.0000	0.00	0.00	-50.00	104.00	144.49	75.69
118	1.0000	0.00	0.00	-53.00	88.00	65.54	114.83
119	1.0000	0.00	0.00	0.00	1148.00	89.99	762.79
120	1.0000	0.00	0.00	-50.00	148.00	535.14	134.74
124	1.0000	0.00	0.00	-57.00	94.00	248.61	512.29
127	1.0075	9040.00	9036.87	0.00	1156.00	128.49	6.42
129	1.0000	0.00	0.00	0.00	474.00	483.29	44.88
130	1.0000	0.00	0.00	0.00	1195.00	726.96	36.35
134	0.9746	1650.00	1642.77	-30.00	50.00	1174.89	253.24
140	1.0000	5620.00	5614.61	-50.00	299.00	157.35	103.07
142	0.9601	7170.00	7168.59	0.00	670.00	2550.68	127.53
144	1.0000	0.00	0.00	-50.00	272.00	76.19	306.65
150	1.0000	0.00	0.00	-56.00	92.00	21.68	148.79

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
151	1.0000	2820.00	2817.06	-15.00	40.00	1151.15	145.34
153	1.0052	0.00	0.00	-50.00	130.00	662.19	33.11
154	1.0349	1500.00	1496.89	-15.00	40.00	784.97	86.79
157	0.9670	0.00	0.00	-50.00	300.00	1796.40	89.82
159	1.0127	0.00	0.00	-30.00	50.00	155.82	7.79
162	0.9913	0.00	0.00	0.00	1999.00	13233.71	661.69
163	0.9696	2310.00	2302.18	-15.00	40.00	1632.49	261.11
164	1.0128	0.00	0.00	-50.00	201.00	1096.68	54.83
166	1.0000	3270.00	3262.09	0.00	323.00	118.59	5.93
167	1.0000	0.00	0.00	-36.00	60.00	31.97	66.04
171	1.0268	0.00	0.00	-50.00	300.00	1445.50	72.27
178	1.0000	0.00	0.00	-50.00	164.00	55.09	48.84
179	1.0000	0.00	0.00	0.00	308.00	439.69	144.52
181	1.0000	0.00	0.00	-33.00	54.00	61.93	20.36
182	1.0258	2700.00	2691.74	0.00	1144.00	1113.05	55.65
186	0.9869	6660.00	6651.15	0.00	962.00	1091.87	714.06
187	1.0000	0.00	0.00	-50.00	137.00	1708.56	85.43
188	1.0000	0.00	0.00	-30.00	50.00	17.32	58.24
189	1.0018	15310.00	15300.35	0.00	1533.00	1635.33	81.77
196	1.0000	0.00	0.00	-50.00	239.00	370.27	121.70
201	1.0000	0.00	0.00	0.00	915.00	3163.77	1492.62
214	1.0000	0.00	0.00	-30.00	50.00	335.25	76.51

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
215	1.0062	1540.00	1534.76	-30.00	50.00	1055.38	109.14
223	1.0037	0.00	0.00	-59.00	97.00	878.60	43.93
224	1.0000	0.00	0.00	0.00	798.00	370.60	1018.70
228	1.0000	0.00	0.00	-50.00	184.00	347.87	114.34
234	1.0000	0.00	0.00	0.00	353.00	4171.09	12.83
239	1.0000	0.00	0.00	-36.00	60.00	75.69	83.09
246	1.0000	0.00	0.00	0.00	837.00	717.16	404.13
248	1.0000	0.00	0.00	0.00	320.00	1366.43	68.32
250	1.0000	0.00	0.00	-30.00	50.00	103.85	34.13
252	1.0000	0.00	0.00	0.00	5015.00	5417.97	1818.63
256	1.0000	0.00	0.00	-35.00	57.00	186.75	61.38
258	1.0000	0.00	0.00	-42.00	69.00	92.21	30.31
261	1.0000	0.00	0.00	-59.00	98.00	202.31	66.49
262	1.0000	0.00	0.00	-44.00	73.00	80.00	54.60
268	1.0000	1240.00	1238.34	-50.00	108.00	1194.11	117.33
276	0.9874	3440.00	3436.14	-15.00	40.00	1120.76	255.98
282	1.0000	0.00	0.00	0.00	1442.00	963.52	1187.69
287	1.0000	0.00	0.00	-33.00	54.00	195.55	64.27
288	0.9871	2770.00	2767.60	-30.00	50.00	2214.15	256.82
301	1.0000	0.00	0.00	-30.00	50.00	127.89	42.03
307	1.0000	0.00	0.00	-50.00	158.00	233.14	76.63
309	1.0000	0.00	0.00	0.00	399.00	2404.70	790.39

Table A.17: Voltage regulated bus data for network of 330 buses and 430 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
314	1.0000	0.00	0.00	-37.00	61.00	201.83	66.34
316	1.0000	0.00	0.00	-30.00	50.00	159.44	52.40
317	1.0000	0.00	0.00	-50.00	133.00	240.92	79.19
319	1.0000	0.00	0.00	-30.00	50.00	191.40	62.91
324	1.0000	0.00	0.00	-50.00	159.00	309.44	101.71
329	1.0000	0.00	0.00	-60.00	99.00	258.44	84.95
330	1.0000	0.00	0.00	0.00	368.00	1161.51	381.77

Table A.18: Load (PQ) bus data

Bus No	P_d (MW)	Q_d (MVA _r)
4	960.00	315.54
10	1277.64	518.93
12	160.91	960.66
22	600.00	197.21
23	1397.12	774.50
26	145.76	1944.10
28	576.52	1080.09
32	746.49	199.94
34	15.79	245.29
36	380.53	1595.34
38	1834.21	987.48
40	507.32	1423.58
41	769.14	950.14
42	508.01	636.60
43	914.55	1222.88
44	7559.76	4516.59
49	61.88	385.88
50	3005.39	1507.56
51	36.46	866.10
52	654.15	2664.67

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
53	46.38	177.76
54	450.10	147.94
55	869.34	285.74
57	13778.16	653.57
58	542.90	769.86
60	943.30	223.77
61	135.49	295.07
63	18.78	309.82
65	724.20	513.77
66	411.38	72.73
67	36.06	819.18
69	686.81	161.86
70	3243.08	1065.95
71	406.96	244.40
72	893.44	2287.34
73	10.24	55.44
74	2835.53	1192.32
76	27.21	43.40
78	727.50	327.31
79	1006.19	435.40

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
82	23.98	32.81
85	2899.71	1286.51
86	674.84	968.45
87	266.33	565.46
88	1540.43	506.32
89	55.37	18.20
90	694.53	228.28
91	116.27	15.08
94	141.34	884.03
97	99.22	1351.29
98	494.40	212.49
99	62.84	20.66
101	176.63	384.02
102	1837.81	1636.71
104	89.62	1141.58
105	1176.58	546.86
106	358.56	1742.88
107	49.42	16.24
108	1076.69	958.15
109	551.86	160.05

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
111	390.05	288.94
113	50.78	16.69
114	52.60	971.60
115	491.42	671.27
117	774.93	3841.44
121	361.67	250.80
122	535.60	446.36
123	5158.04	1695.37
125	120.99	225.06
126	6.22	21.60
128	49.12	401.43
131	423.40	176.19
132	3463.05	1514.02
133	205.70	1969.44
135	22.53	418.45
136	1782.06	1307.72
137	3056.14	1004.50
138	109.81	263.45
139	393.07	142.71
141	403.08	574.26

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
143	639.75	210.28
145	211.82	15.83
146	987.40	738.95
147	184.03	519.41
148	5164.72	2806.97
149	1651.14	529.82
152	195.52	1677.46
155	795.95	261.62
156	30.26	399.34
158	41.39	13.60
160	1876.16	1091.02
161	5028.18	1652.68
165	9.76	48.17
168	924.82	508.85
169	36.92	80.47
170	952.00	312.91
172	833.66	274.01
173	57.48	64.45
174	288.09	61.87
175	893.67	293.73

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
176	565.47	185.86
177	973.53	285.70
180	3118.69	1025.06
183	594.67	195.46
184	383.25	1353.77
185	3540.47	1163.70
190	3056.60	1004.65
191	112.13	36.86
192	51.69	61.98
193	826.59	271.69
194	69.69	22.91
195	592.45	194.73
197	42.94	14.11
198	10.39	124.39
199	322.99	72.72
200	2676.24	879.64
202	1966.24	1222.79
203	45.56	193.15
204	4248.27	1396.34
205	121.91	64.52

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
206	448.22	147.32
207	62.84	50.83
208	2490.45	818.57
209	65.43	81.61
210	643.43	211.48
211	134.37	67.83
212	14.14	82.23
213	1494.00	491.06
216	13903.16	1176.84
217	230.15	175.93
218	2319.55	1439.84
219	863.71	159.61
220	19.33	41.61
221	65.66	21.58
222	34.12	82.96
225	672.88	221.17
226	79.50	26.13
227	10.37	28.29
229	239.13	634.93
230	46.60	15.32

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
231	414.93	201.02
232	750.58	246.70
233	435.66	29.75
235	1816.54	597.07
236	155.00	106.36
237	84.50	1133.81
238	164.23	263.44
240	45.24	14.87
241	151.31	49.73
242	1537.38	1411.68
243	2631.87	865.05
244	258.10	146.93
245	14.02	42.18
247	1361.74	447.58
249	1161.14	381.65
251	67.22	22.09
253	44.57	14.65
254	322.09	767.45
255	67.64	69.79
257	76.97	25.30

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVar)
259	846.81	278.33
260	82.54	27.13
263	341.29	450.67
264	46.25	188.92
265	49.52	16.28
266	493.02	193.61
267	67.17	835.69
269	265.87	210.30
270	64.81	21.30
271	617.08	202.83
272	796.11	261.67
273	1250.94	281.03
274	1236.89	406.55
275	1360.63	447.22
277	610.55	221.01
278	185.72	61.04
279	7.35	48.14
280	326.31	107.25
281	853.60	1585.24
283	115.35	37.92

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVar)
284	479.13	283.82
285	1621.70	141.65
286	113.68	37.37
289	539.31	177.26
290	135.62	44.58
291	1612.44	646.80
292	118.43	38.93
293	389.27	199.37
294	43.34	14.24
295	54.86	18.03
296	1412.08	464.13
297	16.97	140.97
298	1035.59	340.38
299	95.89	31.52
300	404.14	526.45
302	111.11	36.52
303	768.61	252.63
304	403.45	132.61
305	3027.87	973.05
306	208.07	68.39

Table A.18: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
308	1972.63	648.37
310	353.77	116.28
311	52.29	53.72
312	814.75	267.79
313	121.30	39.87
315	1493.18	490.78
318	1853.84	609.33
320	609.47	200.32
321	601.27	197.63
322	90.94	166.22
323	100.25	32.95
325	190.76	62.70
326	407.15	133.82
327	236.98	94.95
328	72.48	23.82

Load-Flow Solution

Table A.19: Load-flow solution for the 330-bus and 430-line network.

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
1**	36753.85	2123.91	6520.00	326.00	1.0000	0.0000
2	14060.50	2479.46	9208.88	1981.53	1.0000	-0.0481
3	5219.65	0.00	2800.00	91.73	1.0000	-0.0734
4	0.00	0.00	960.00	315.54	1.0097	-0.1163
5	0.00	1070.52	564.57	1187.23	1.0100	-0.1455
6	2603.95	0.00	1063.47	297.95	1.0062	-0.1514
7	2966.84	0.00	705.99	4461.50	1.0000	-0.1540
8	7983.68	0.00	4960.00	4288.38	1.0000	-0.1194
9	4469.93	0.00	3440.00	1312.35	1.0000	-0.0774
10	0.00	0.00	1277.64	518.93	1.0006	-0.0420
11	0.00	665.17	6355.66	317.78	1.0015	-0.0006
12	0.00	0.00	160.91	960.66	0.9979	0.0462
13	5986.74	0.05	680.14	2294.17	0.9977	0.0493
14	6661.56	0.00	3560.00	1236.10	1.0000	0.1077
15	5352.81	0.00	898.89	1169.92	1.0000	0.1233
16	0.00	590.56	6437.84	321.89	1.0046	0.1818
17	21183.83	0.00	8040.00	1252.37	1.0000	0.2595
18	5841.17	74.16	134.64	867.53	1.0000	0.3211
19	22249.40	563.94	1032.20	51.61	1.0000	0.3387
20	2203.62	0.00	1367.19	337.63	1.0059	0.2659

**Bus number 1 is selected as a slack and reference bus, for this load-flow solution

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
21	6031.08	0.00	1404.47	1189.33	0.9969	0.1703
22	0.00	0.00	600.00	197.21	0.9939	0.1541
23	0.00	0.00	1397.12	774.50	0.9904	0.1344
24	27450.42	3104.49	9200.00	1051.79	1.0000	0.1537
25	16932.91	0.00	3689.69	2134.61	1.0000	0.1702
26	0.00	0.00	145.76	1944.10	1.0046	0.0783
27	3967.38	0.00	1028.56	1545.26	1.0061	0.0207
28	0.00	0.00	576.52	1080.09	1.0153	0.0085
29	2835.44	0.04	1201.69	777.88	1.0228	0.0384
30	12687.68	0.00	336.12	1174.84	1.0154	0.0711
31	7284.10	0.03	955.23	1273.87	1.0001	0.0339
32	0.00	0.00	746.49	199.94	0.9959	-0.3494
33	6246.87	58.80	700.96	35.05	0.9973	0.1461
34	0.00	0.00	15.79	245.29	1.0000	-0.0992
35	2417.27	0.00	3680.81	848.03	1.0008	0.0438
36	0.00	0.00	380.53	1595.34	1.0088	-0.0186
37	4251.98	0.03	1011.43	343.28	1.0066	-0.0338
38	0.00	0.00	1834.21	987.48	0.9954	-0.2000
39	4936.78	0.01	1566.58	1463.08	0.9928	0.2362
40	0.00	0.00	507.32	1423.58	1.0239	-0.0278
41	0.00	0.00	769.14	950.14	0.9755	-0.2000
42	0.00	0.00	508.01	636.60	1.0221	-0.0645

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
43	0.00	0.00	914.55	1222.88	0.9950	0.1342
44	0.00	0.00	7559.76	4516.59	0.9839	-0.0990
45	3704.44	0.02	1922.69	1238.17	0.9989	0.2465
46	2756.30	0.02	790.18	513.95	1.0049	-0.0469
47	0.00	186.33	256.40	12.82	1.0000	-0.5188
48	0.00	2780.77	5089.40	254.47	1.0081	-0.2812
49	0.00	0.00	61.88	385.88	0.9945	0.0174
50	0.00	0.00	3005.39	1507.56	1.0021	-0.0486
51	0.00	0.00	36.46	866.10	1.0063	-0.0340
52	0.00	0.00	654.15	2664.67	0.9755	0.0806
53	0.00	0.00	46.38	177.76	1.0000	-0.0958
54	0.00	0.00	450.10	147.94	1.0241	-0.0774
55	0.00	0.00	869.34	285.74	0.9944	0.1187
56	0.00	255.05	422.72	138.94	1.0000	-0.6583
57	0.00	0.00	13778.16	653.57	0.9993	-0.1361
58	0.00	0.00	542.90	769.86	0.9673	0.0032
59	5438.20	0.01	488.07	348.35	1.0066	0.0663
60	0.00	0.00	943.30	223.77	1.0000	-0.3071
61	0.00	0.00	135.49	295.07	1.0006	0.0368
62	5045.43	0.00	669.18	3829.55	0.9776	-0.2336
63	0.00	0.00	18.78	309.82	0.9812	-0.6046
64	6127.94	0.00	1404.68	396.33	1.0000	-0.1318

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
65	0.00	0.00	724.20	513.77	1.0058	0.0101
66	0.00	0.00	411.38	72.73	1.0000	-0.5123
67	0.00	0.00	36.06	819.18	0.9779	-0.1005
68	0.00	57.30	393.21	305.97	1.0000	-0.3014
69	0.00	0.00	686.81	161.86	1.0015	-0.0047
70	0.00	0.00	3243.08	1065.95	0.9770	0.0719
71	0.00	0.00	406.96	244.40	1.0000	-0.1012
72	0.00	0.00	893.44	2287.34	0.9823	0.1671
73	0.00	0.00	10.24	55.44	0.9920	-0.1972
74	0.00	0.00	2835.53	1192.32	0.9985	0.2553
75	16520.53	2398.53	740.25	37.01	0.9933	-0.0669
76	0.00	0.00	27.21	43.40	0.9801	-0.4521
77	3622.39	0.00	1114.92	773.08	0.9956	0.1479
78	0.00	0.00	727.50	327.31	0.9848	-0.5642
79	0.00	0.00	1006.19	435.40	1.0220	-0.1384
80	0.00	1097.62	1227.67	61.38	1.0000	-0.3207
81	0.00	1196.78	456.43	22.82	1.0000	0.0336
82	0.00	0.00	23.98	32.81	1.0188	-0.4305
83	1254.81	103.47	1920.18	22.85	1.0000	-0.4453
84	0.00	868.83	336.66	542.38	1.0000	-0.0712
85	0.00	0.00	2899.71	1286.51	1.0009	-0.0006
86	0.00	0.00	674.84	968.45	0.9800	-0.1109

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
87	0.00	0.00	266.33	565.46	0.9590	-0.6783
88	0.00	0.00	1540.43	506.32	1.0115	-0.1543
89	0.00	0.00	55.37	18.20	1.0048	-0.1888
90	0.00	0.00	694.53	228.28	0.9991	0.1493
91	0.00	0.00	116.27	15.08	0.9919	-0.0735
92	2884.00	306.71	1138.69	56.93	1.0011	-0.2783
93	0.00	32.58	684.22	33.28	1.0000	-0.3228
94	0.00	0.00	141.34	884.03	1.0047	0.1896
95	1622.25	0.00	932.26	159.39	1.0000	-0.2152
96	0.00	336.08	17.55	325.89	1.0000	-0.8456
97	0.00	0.00	99.22	1351.29	0.9919	-0.2133
98	0.00	0.00	494.40	212.49	0.9922	-0.1333
99	0.00	0.00	62.84	20.66	0.9793	-0.4579
100	4560.36	0.01	205.83	2577.92	0.9783	0.0843
101	0.00	0.00	176.63	384.02	1.0030	-0.0549
102	0.00	0.00	1837.81	1636.71	0.9556	-0.0190
103	0.00	240.39	1888.45	94.42	0.9991	-0.3248
104	0.00	0.00	89.62	1141.58	0.9868	-0.0976
105	0.00	0.00	1176.58	546.86	1.0075	0.0154
106	0.00	0.00	358.56	1742.88	0.9745	-0.0330
107	0.00	0.00	49.42	16.24	0.9927	-0.2040
108	0.00	0.00	1076.69	958.15	0.9758	-0.4034

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
109	0.00	0.00	551.86	160.05	0.9996	-0.3282
110	2471.98	0.03	540.09	583.58	0.9722	-0.1270
111	0.00	0.00	390.05	288.94	0.9736	-0.1689
112	2662.58	0.00	1480.49	242.84	0.9936	-0.0104
113	0.00	0.00	50.78	16.69	0.9869	-0.1795
114	0.00	0.00	52.60	971.60	0.9916	0.1061
115	0.00	0.00	491.42	671.27	0.9969	-0.0327
116	0.00	94.36	144.49	75.69	1.0000	-0.5622
117	0.00	0.00	774.93	3841.44	0.9696	-0.1598
118	0.00	79.34	65.54	114.83	1.0000	-0.2532
119	0.00	1147.54	89.99	762.79	1.0000	-0.1234
120	0.00	134.32	535.14	134.74	1.0000	-0.8279
121	0.00	0.00	361.67	250.80	0.9578	-0.0300
122	0.00	0.00	535.60	446.36	0.9955	0.0878
123	0.00	0.00	5158.04	1695.37	0.9801	0.0938
124	0.00	85.13	248.61	512.29	1.0000	-0.4747
125	0.00	0.00	120.99	225.06	0.9953	0.0381
126	0.00	0.00	6.22	21.60	0.9671	-0.3097
127	9036.87	1155.48	128.49	6.42	1.0075	0.0220
128	0.00	0.00	49.12	401.43	0.9902	-0.2168
129	0.00	473.42	483.29	44.88	1.0000	-1.2138
130	0.00	1194.62	726.96	36.35	1.0000	-0.7126

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
131	0.00	0.00	423.40	176.19	0.9825	-0.2070
132	0.00	0.00	3463.05	1514.02	0.9923	-0.0920
133	0.00	0.00	205.70	1969.44	0.9508	-0.1215
134	1642.77	0.00	1174.89	253.24	0.9746	-0.4671
135	0.00	0.00	22.53	418.45	1.0059	-0.0326
136	0.00	0.00	1782.06	1307.72	0.9813	-0.1617
137	0.00	0.00	3056.14	1004.50	0.9530	-0.3293
138	0.00	0.00	109.81	263.45	1.0006	-0.0936
139	0.00	0.00	393.07	142.71	1.0049	-0.0112
140	5614.61	271.61	157.35	103.07	1.0000	-0.8690
141	0.00	0.00	403.08	574.26	0.9775	-0.3314
142	7168.59	669.97	2550.68	127.53	0.9601	-0.1935
143	0.00	0.00	639.75	210.28	1.0095	-0.0600
144	0.00	246.42	76.19	306.65	1.0000	-0.6682
145	0.00	0.00	211.82	15.83	1.0082	-0.1775
146	0.00	0.00	987.40	738.95	0.9899	-0.3467
147	0.00	0.00	184.03	519.41	0.9981	-0.0693
148	0.00	0.00	5164.72	2806.97	0.9808	-0.1198
149	0.00	0.00	1651.14	529.82	0.9951	-0.0267
150	0.00	83.32	21.68	148.79	1.0000	-0.7147
151	2817.06	0.00	1151.15	145.34	1.0000	0.0027
152	0.00	0.00	195.52	1677.46	0.9649	-0.0402

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
153	0.00	117.79	662.19	33.11	1.0052	-0.7646
154	1496.89	0.00	784.97	86.79	1.0349	-0.2193
155	0.00	0.00	795.95	261.62	1.0120	0.1452
156	0.00	0.00	30.26	399.34	0.9834	-0.7967
157	0.00	279.25	1796.40	89.82	0.9670	-0.6014
158	0.00	0.00	41.39	13.60	0.9605	-0.3794
159	0.00	14.79	155.82	7.79	1.0127	-0.3911
160	0.00	0.00	1876.16	1091.02	0.9900	-0.8635
161	0.00	0.00	5028.18	1652.68	0.9604	-0.1723
162	0.00	1998.06	13233.71	661.69	0.9913	-0.1277
163	2302.18	0.00	1632.49	261.11	0.9696	-0.0723
164	0.00	182.68	1096.68	54.83	1.0128	-0.6841
165	0.00	0.00	9.76	48.17	1.0182	-0.4335
166	3262.09	322.55	118.59	5.93	1.0000	-0.2230
167	0.00	54.46	31.97	66.04	1.0000	-0.5810
168	0.00	0.00	924.82	508.85	0.9557	-0.2976
169	0.00	0.00	36.92	80.47	0.9864	-0.8274
170	0.00	0.00	952.00	312.91	0.9510	-0.0402
171	0.00	299.71	1445.50	72.27	1.0268	-0.2292
172	0.00	0.00	833.66	274.01	1.0087	-0.1749
173	0.00	0.00	57.48	64.45	1.0010	-0.8839
174	0.00	0.00	288.09	61.87	0.9763	-0.7551

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
175	0.00	0.00	893.67	293.73	0.9979	0.1269
176	0.00	0.00	565.47	185.86	0.9919	-0.1067
177	0.00	0.00	973.53	285.70	0.9961	-0.1259
178	0.00	148.96	55.09	48.84	1.0000	-1.3725
179	0.00	307.17	439.69	144.52	1.0000	-0.8371
180	0.00	0.00	3118.69	1025.06	0.9529	-0.0791
181	0.00	48.89	61.93	20.36	1.0000	-0.1282
182	2691.74	1143.23	1113.05	55.65	1.0258	-0.8166
183	0.00	0.00	594.67	195.46	0.9938	0.0276
184	0.00	0.00	383.25	1353.77	0.9928	-0.0343
185	0.00	0.00	3540.47	1163.70	0.9842	-1.3307
186	6651.15	961.20	1091.87	714.06	0.9869	-0.1107
187	0.00	123.71	1708.56	85.43	1.0000	-0.4090
188	0.00	41.43	17.32	58.24	1.0000	-0.7060
189	15300.35	1532.74	1635.33	81.77	1.0018	0.1410
190	0.00	0.00	3056.60	1004.65	0.9618	-0.2851
191	0.00	0.00	112.13	36.86	1.0028	-0.7724
192	0.00	0.00	51.69	61.98	0.9964	-0.7227
193	0.00	0.00	826.59	271.69	0.9545	-0.4485
194	0.00	0.00	69.69	22.91	1.0072	-0.2110
195	0.00	0.00	592.45	194.73	1.0049	-0.0461
196	0.00	216.82	370.27	121.70	1.0000	-0.6710

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
197	0.00	0.00	42.94	14.11	1.0186	-0.4381
198	0.00	0.00	10.39	124.39	1.0000	-0.9227
199	0.00	0.00	322.99	72.72	1.0129	-0.3443
200	0.00	0.00	2676.24	879.64	0.9378	-0.3511
201	0.00	914.45	3163.77	1492.62	1.0000	-0.4158
202	0.00	0.00	1966.24	1222.79	0.9681	-0.4288
203	0.00	0.00	45.56	193.15	1.0090	-0.5326
204	0.00	0.00	4248.27	1396.34	0.9573	-0.3123
205	0.00	0.00	121.91	64.52	1.0000	-0.9036
206	0.00	0.00	448.22	147.32	0.9835	-0.1354
207	0.00	0.00	62.84	50.83	1.0000	-0.1288
208	0.00	0.00	2490.45	818.57	0.9427	-0.3365
209	0.00	0.00	65.43	81.61	1.0021	-0.0835
210	0.00	0.00	643.43	211.48	1.0227	-0.0419
211	0.00	0.00	134.37	67.83	1.0000	-0.7915
212	0.00	0.00	14.14	82.23	0.9804	-0.9986
213	0.00	0.00	1494.00	491.06	0.9952	-0.0273
214	0.00	36.43	335.25	76.51	1.0000	-0.7117
215	1534.76	0.00	1055.38	109.14	1.0062	-0.0468
216	0.00	0.00	13903.16	1176.84	0.9813	-0.1424
217	0.00	0.00	230.15	175.93	0.9642	-0.0475
218	0.00	0.00	2319.55	1439.84	0.9759	0.1716

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
219	0.00	0.00	863.71	159.61	1.0000	-0.2902
220	0.00	0.00	19.33	41.61	1.0012	-0.9377
221	0.00	0.00	65.66	21.58	0.9876	-0.8394
222	0.00	0.00	34.12	82.96	0.9835	-0.0535
223	0.00	87.47	878.60	43.93	1.0037	-0.6141
224	0.00	797.02	370.60	1018.70	1.0000	-0.0688
225	0.00	0.00	672.88	221.17	1.0227	-0.3047
226	0.00	0.00	79.50	26.13	0.9992	-0.5921
227	0.00	0.00	10.37	28.29	1.0006	-0.9427
228	0.00	166.82	347.87	114.34	1.0000	-0.6456
229	0.00	0.00	239.13	634.93	0.9857	0.0372
230	0.00	0.00	46.60	15.32	1.0002	-0.9456
231	0.00	0.00	414.93	201.02	0.9897	-0.9409
232	0.00	0.00	750.58	246.70	0.9967	-0.0930
233	0.00	0.00	435.66	29.75	1.0000	-0.4047
234	0.00	352.16	4171.09	12.83	1.0000	-0.9992
235	0.00	0.00	1816.54	597.07	0.9688	-0.3542
236	0.00	0.00	155.00	106.36	1.0000	-0.2816
237	0.00	0.00	84.50	1133.81	0.9592	-0.5428
238	0.00	0.00	164.23	263.44	0.9886	-0.1496
239	0.00	54.04	75.69	83.09	1.0000	-0.8667
240	0.00	0.00	45.24	14.87	1.0207	-0.1010

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
241	0.00	0.00	151.31	49.73	0.9561	-0.3986
242	0.00	0.00	1537.38	1411.68	0.9763	0.1244
243	0.00	0.00	2631.87	865.05	0.9841	-0.1347
244	0.00	0.00	258.10	146.93	0.9599	-0.7701
245	0.00	0.00	14.02	42.18	1.0000	-0.3008
246	0.00	836.83	717.16	404.13	1.0000	-0.6249
247	0.00	0.00	1361.74	447.58	0.9682	-0.2427
248	0.00	319.79	1366.43	68.32	1.0000	-0.3505
249	0.00	0.00	1161.14	381.65	0.9847	-0.1626
250	0.00	31.79	103.85	34.13	1.0000	-0.1899
251	0.00	0.00	67.22	22.09	1.0074	-0.1697
252	0.00	5014.37	5417.97	1818.63	1.0000	-0.2355
253	0.00	0.00	44.57	14.65	0.9996	-0.9255
254	0.00	0.00	322.09	767.45	1.0045	-0.0123
255	0.00	0.00	67.64	69.79	0.9989	-0.6422
256	0.00	51.71	186.75	61.38	1.0000	-1.1959
257	0.00	0.00	76.97	25.30	0.9817	-1.0151
258	0.00	62.44	92.21	30.31	1.0000	-0.6887
259	0.00	0.00	846.81	278.33	1.0055	-0.0501
260	0.00	0.00	82.54	27.13	0.9990	-0.3039
261	0.00	88.46	202.31	66.49	1.0000	-0.9651
262	0.00	65.82	80.00	54.60	1.0000	-1.2357

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
263	0.00	0.00	341.29	450.67	0.9778	-1.3031
264	0.00	0.00	46.25	188.92	0.9994	-0.0757
265	0.00	0.00	49.52	16.28	0.9805	-1.2913
266	0.00	0.00	493.02	193.61	0.9882	-0.0665
267	0.00	0.00	67.17	835.69	0.9875	-0.0686
268	1238.34	97.70	1194.11	117.33	1.0000	-0.4747
269	0.00	0.00	265.87	210.30	0.9820	0.1606
270	0.00	0.00	64.81	21.30	1.0149	-0.7753
271	0.00	0.00	617.08	202.83	1.0000	-0.4346
272	0.00	0.00	796.11	261.67	0.9851	0.0734
273	0.00	0.00	1250.94	281.03	0.9651	-0.0566
274	0.00	0.00	1236.89	406.55	0.9823	-0.1824
275	0.00	0.00	1360.63	447.22	0.9602	-0.1997
276	3436.14	0.00	1120.76	255.98	0.9874	-0.8391
277	0.00	0.00	610.55	221.01	0.9721	-0.2952
278	0.00	0.00	185.72	61.04	0.9959	-1.3834
279	0.00	0.00	7.35	48.14	0.9996	-1.3735
280	0.00	0.00	326.31	107.25	0.9959	-0.2602
281	0.00	0.00	853.60	1585.24	0.9614	0.0633
282	0.00	1441.01	963.52	1187.69	1.0000	-0.2102
283	0.00	0.00	115.35	37.92	1.0227	-0.0189
284	0.00	0.00	479.13	283.82	0.9647	-0.2213

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
285	0.00	0.00	1621.70	141.65	1.0000	-0.2880
286	0.00	0.00	113.68	37.37	0.9978	-0.2364
287	0.00	49.01	195.55	64.27	1.0000	-0.3806
288	2767.60	0.00	2214.15	256.82	0.9871	-0.2300
289	0.00	0.00	539.31	177.26	0.9889	0.0159
290	0.00	0.00	135.62	44.58	0.9678	-0.6516
291	0.00	0.00	1612.44	646.80	1.0001	-0.0206
292	0.00	0.00	118.43	38.93	0.9968	-0.8844
293	0.00	0.00	389.27	199.37	0.9738	-1.3835
294	0.00	0.00	43.34	14.24	1.0001	-1.3786
295	0.00	0.00	54.86	18.03	1.0130	-0.3773
296	0.00	0.00	1412.08	464.13	0.9597	-0.2374
297	0.00	0.00	16.97	140.97	1.0000	-1.4725
298	0.00	0.00	1035.59	340.38	0.9961	0.2182
299	0.00	0.00	95.89	31.52	0.9981	-1.2425
300	0.00	0.00	404.14	526.45	0.9744	-0.7939
301	0.00	44.84	127.89	42.03	1.0000	-1.6016
302	0.00	0.00	111.11	36.52	1.0008	-1.5013
303	0.00	0.00	768.61	252.63	0.9993	-0.2374
304	0.00	0.00	403.45	132.61	0.9962	-0.4190
305	0.00	0.00	3027.87	973.05	0.9714	-0.2974
306	0.00	0.00	208.07	68.39	1.0024	-0.2089

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
307	0.00	142.98	233.14	76.63	1.0000	-1.1510
308	0.00	0.00	1972.63	648.37	0.9606	0.0831
309	0.00	398.39	2404.70	790.39	1.0000	-0.9956
310	0.00	0.00	353.77	116.28	0.9553	-0.5627
311	0.00	0.00	52.29	53.72	1.0013	-0.3160
312	0.00	0.00	814.75	267.79	1.0084	-0.2584
313	0.00	0.00	121.30	39.87	0.9591	-0.5629
314	0.00	54.68	201.83	66.34	1.0000	-0.3351
315	0.00	0.00	1493.18	490.78	0.9505	-0.8800
316	0.00	45.00	159.44	52.40	1.0000	-0.3684
317	0.00	120.67	240.92	79.19	1.0000	-0.6910
318	0.00	0.00	1853.84	609.33	0.9602	-0.0305
319	0.00	34.07	191.40	62.91	1.0000	-0.3758
320	0.00	0.00	609.47	200.32	0.9915	-0.0957
321	0.00	0.00	601.27	197.63	0.9949	-0.2376
322	0.00	0.00	90.94	166.22	1.0001	-0.9461
323	0.00	0.00	100.25	32.95	0.9698	-0.2928
324	0.00	143.95	309.44	101.71	1.0000	-0.3858
325	0.00	0.00	190.76	62.70	0.9888	-0.3623
326	0.00	0.00	407.15	133.82	0.9954	-0.9681
327	0.00	0.00	236.98	94.95	0.9792	-0.1739
328	0.00	0.00	72.48	23.82	0.9954	-0.7310

Table A.19: Load-flow solution for the 330-bus and 430-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
329	0.00	89.34	258.44	84.95	1.0000	-0.2984
330	0.00	367.07	1161.51	381.77	1.0000	-0.6578

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows.

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
1	1 - 2	7746.04	-387.14	19.55	0.7924	0.1086	0.2566
2	2 - 3	5865.94	-209.78	19.55	1.0002	0.0571	0.3237
3	3 - 4	4966.10	-2244.68	19.55	0.3175	0.0970	0.1127
4	4 - 5	3998.04	-651.61	19.55	0.3408	0.0672	0.1106
5	5 - 6	713.91	266.53	19.55	0.1217	0.0139	0.0416
6	6 - 7	273.72	417.24	19.55	0.0467	0.0064	0.0273
7	7 - 8	-1846.36	-3527.09	19.55	-0.1349	-0.0781	0.0941
8	8 - 9	-3808.71	-539.13	19.55	-0.3247	-0.0946	0.1061
9	9 - 10	-3594.75	-169.62	19.55	-0.4597	-0.0801	0.1488
10	10 - 11	-5159.31	-207.11	19.55	-0.5278	-0.0935	0.1707
11	11 - 12	-5606.79	201.97	19.55	-0.4780	-0.1051	0.1545
12	12 - 13	-7256.38	538.01	19.55	-1.2372	-0.0071	0.4021
13	13 - 14	-8777.18	30.20	19.55	-1.1224	-0.1314	0.3638
14	14 - 15	-9033.43	364.29	19.55	-1.5402	-0.0352	0.4986
15	15 - 16	-6866.70	-353.82	19.55	-0.8781	-0.1329	0.2844
16	16 - 17	-8281.02	-692.03	19.55	-0.4236	-0.1754	0.1368
17	17 - 18	-5427.80	275.46	19.55	-1.3882	-0.1388	0.4496
18	18 - 19	-678.63	-167.26	19.55	-0.1736	-0.0397	0.0578
19	19 - 20	5125.87	-848.55	19.55	0.6555	0.1648	0.2149
20	20 - 21	4592.41	-521.32	19.55	0.4698	0.2174	0.1520
21	21 - 22	2376.76	319.63	19.55	0.6079	0.0365	0.1990
22	22 - 23	1775.34	185.64	19.55	0.4541	0.0441	0.1486
23	23 - 24	-1465.89	-749.89	19.55	-0.3749	-0.0439	0.1375
24	24 - 25	-1020.01	-78.51	19.55	-0.2609	-0.0373	0.0846

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
25	25 - 26	7644.24	-1772.73	19.55	0.4888	0.2080	0.1623
26	26 - 27	4498.88	-546.23	19.55	0.5753	0.1315	0.1866
27	27 - 28	1249.61	-1072.24	19.55	0.3196	0.0274	0.1354
28	28 - 29	-2351.33	-2128.65	19.55	-0.1503	-0.0709	0.0646
29	29 - 30	-3714.13	734.81	19.55	-0.4750	-0.0760	0.1531
30	30 - 1	6081.24	930.99	19.55	0.7777	0.1644	0.2506
31	13 - 31	471.77	-330.31	19.55	0.1207	0.0345	0.0477
32	9 - 32	171.79	-52.44	8.22	0.1045	0.0231	0.0370
33	24 - 33	2143.91	668.32	19.55	0.5483	0.0172	0.1858
34	14 - 34	130.03	-95.35	8.22	0.0791	0.0242	0.0332
35	26 - 35	987.31	-182.73	19.55	0.2525	0.0786	0.0827
36	27 - 36	824.79	-443.44	19.55	0.2109	0.0898	0.0770
37	29 - 36	1835.63	169.30	19.55	0.4695	0.1341	0.1491
38	12 - 31	1388.18	-357.99	19.55	0.3550	0.0274	0.1188
39	36 - 37	726.83	-81.03	19.55	0.1859	0.0350	0.0600
40	7 - 38	1100.02	-222.25	19.55	0.2813	0.1037	0.0928
41	17 - 39	1572.11	330.38	19.55	0.4021	0.0528	0.1329
42	31 - 11	6284.26	-425.08	19.55	1.6072	0.0780	0.5210
43	29 - 40	1158.27	-500.16	19.55	0.2962	0.1565	0.1020
44	40 - 42	959.59	-290.57	19.55	0.2454	0.0869	0.0810
45	8 - 38	2823.38	-42.89	19.55	0.7221	0.1815	0.2336
46	24 - 43	1116.13	124.17	19.55	0.2855	0.0440	0.0929
47	2 - 44	2235.88	516.32	19.55	0.5718	0.1143	0.1898

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
48	17 - 45	591.70	-133.30	19.55	0.1513	0.0294	0.0502
49	3 - 44	3314.17	1942.96	19.55	0.8476	0.0581	0.3178
50	37 - 46	650.97	-92.24	19.55	0.1665	0.0300	0.0540
51	8 - 47	250.68	-19.60	8.22	0.1525	0.0301	0.0518
52	38 - 48	1057.11	-739.70	19.55	0.2704	0.1803	0.1072
53	7 - 47	1966.79	229.52	8.22	0.4785	0.0677	0.1633
54	13 - 49	926.74	-185.41	19.55	0.2370	0.0718	0.0784
55	28 - 50	1644.62	84.51	19.55	0.4206	0.1322	0.1342
56	28 - 51	1378.92	18.67	19.55	0.3527	0.0987	0.1124
57	30 - 40	1127.71	-794.49	19.55	0.2884	0.2267	0.1124
58	23 - 52	1842.83	290.43	19.55	0.4713	0.1185	0.1558
59	12 - 53	91.01	-63.63	8.22	0.0554	0.0108	0.0229
60	42 - 54	450.32	-321.61	19.55	0.1152	0.0303	0.0448
61	10 - 53	282.35	-6.19	8.22	0.0859	0.0020	0.0291
62	33 - 55	870.20	-165.24	19.55	0.2226	0.0617	0.0735
63	35 - 56	422.99	116.34	8.22	0.2573	0.0281	0.0904
64	2 - 57	1941.48	-747.18	19.55	0.3310	0.1962	0.1147
65	49 - 53	345.83	-31.44	8.22	0.2104	0.0198	0.0720
66	52 - 58	1334.15	-250.79	19.55	0.3412	0.1657	0.1151
67	26 - 59	414.05	-308.28	19.55	0.1059	0.0272	0.0425
68	46 - 60	163.57	-86.55	8.22	0.0995	0.0308	0.0380
69	46 - 57	1756.34	-269.20	19.55	0.4492	0.2027	0.1463
70	35 - 61	401.72	-132.21	19.55	0.1027	0.0158	0.0350

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
71	8 - 62	1909.70	-28.89	19.55	0.4884	0.2539	0.1580
72	47 - 63	1114.36	9.17	8.22	0.4519	0.1972	0.1532
73	33 - 52	5246.92	1660.72	19.55	1.3419	0.1456	0.4565
74	37 - 64	63.94	-47.61	8.22	0.0389	0.0060	0.0163
75	30 - 65	1423.88	-130.53	19.55	0.3642	0.1415	0.1165
76	60 - 66	105.91	-76.78	3.18	0.1665	0.1143	0.0755
77	45 - 16	2704.53	-431.71	19.55	0.6917	0.1462	0.2268
78	1 - 67	1926.40	64.19	19.55	0.4927	0.2237	0.1594
79	49 - 68	203.22	-16.51	8.22	0.1236	0.0160	0.0423
80	26 - 69	1318.95	-432.14	19.55	0.3373	0.1888	0.1143
81	1 - 41	8625.35	1460.01	19.55	2.2060	0.4411	0.7236
82	24 - 70	3253.26	517.81	19.55	0.5547	0.1822	0.1817
83	35 - 71	93.16	-63.94	8.22	0.0567	0.0114	0.0233
84	17 - 72	2632.59	-58.77	19.55	0.4489	0.2064	0.1452
85	64 - 60	1591.54	-85.21	8.22	0.9681	0.4052	0.3286
86	71 - 73	59.73	-10.59	3.18	0.0939	0.0139	0.0350
87	17 - 74	1194.57	343.93	19.55	0.3055	0.0096	0.1028
88	2 - 75	2541.04	771.62	19.55	0.6499	0.0427	0.2197
89	38 - 62	1022.12	275.30	19.55	0.2614	0.0754	0.0880
90	68 - 76	90.19	-7.93	3.18	0.1418	0.0302	0.0522
91	25 - 77	972.32	-7.38	19.55	0.2487	0.0504	0.0804
92	47 - 78	932.59	222.70	8.22	0.5673	0.1054	0.1977
93	6 - 47	376.51	-217.17	8.22	0.2290	0.1813	0.0891

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
94	43 - 79	174.42	-87.60	8.22	0.1061	0.0285	0.0404
95	26 - 80	254.08	4.56	8.22	0.1545	0.0214	0.0522
96	20 - 81	152.81	-0.48	8.22	0.0929	0.0058	0.0313
97	25 - 43	910.36	-190.63	19.55	0.2328	0.0811	0.0769
98	68 - 82	76.83	-47.60	3.18	0.1208	0.0400	0.0522
99	67 - 83	218.12	3.67	8.22	0.1327	0.0078	0.0460
100	24 - 84	4821.37	-1046.91	19.55	0.6165	0.4945	0.2041
101	62 - 32	138.14	-97.25	8.22	0.0840	0.0206	0.0356
102	14 - 85	1395.05	-578.49	19.55	0.3568	0.2409	0.1249
103	44 - 86	1444.59	374.51	19.55	0.3695	0.0264	0.1255
104	63 - 87	891.44	162.36	8.22	0.5422	0.1630	0.1904
105	19 - 81	3249.30	400.42	8.22	0.4941	0.0320	0.1688
106	36 - 88	1547.95	-674.46	19.55	0.3959	0.3059	0.1385
107	34 - 89	55.40	-24.61	3.18	0.0871	0.0168	0.0350
108	25 - 90	695.05	-216.00	19.55	0.1778	0.0472	0.0602
109	1 - 57	6885.43	105.14	19.55	1.7610	0.3068	0.5696
110	75 - 91	576.12	22.96	19.55	0.1473	0.0147	0.0480
111	64 - 92	659.25	-288.07	8.22	0.4010	0.3319	0.1483
112	79 - 93	122.69	20.85	3.18	0.1929	0.0076	0.0703
113	13 - 85	2697.43	-339.60	19.55	0.6899	0.1123	0.2254
114	45 - 94	940.54	-563.99	19.55	0.2405	0.1285	0.0908
115	79 - 95	46.21	-27.19	3.18	0.0727	0.0236	0.0303
116	91 - 96	459.71	174.24	8.22	0.2796	0.0058	0.1022

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
117	59 - 69	4438.27	194.09	19.55	1.1351	0.1621	0.3651
118	7 - 97	1313.95	-171.08	19.55	0.3360	0.1334	0.1096
119	53 - 98	552.10	-49.69	9.65	0.2861	0.0947	0.1110
120	76 - 99	62.88	-13.79	3.18	0.0989	0.0146	0.0379
121	19 - 74	2127.94	-248.86	19.55	0.5442	0.1881	0.1772
122	25 - 100	2000.64	203.68	19.55	0.5117	0.1914	0.1663
123	46 - 101	696.89	55.65	19.55	0.1782	0.0183	0.0575
124	52 - 102	3525.43	7.33	19.55	0.4508	0.2112	0.1495
125	27 - 80	2967.40	449.62	8.22	0.5157	0.0441	0.1757
126	60 - 103	267.01	-86.90	8.22	0.1624	0.0412	0.0579
127	69 - 104	3297.15	-296.99	19.55	0.4216	0.2083	0.1367
128	14 - 105	1814.36	-1005.41	19.55	0.3094	0.2063	0.1144
129	19 - 72	10035.04	1425.17	19.55	2.5665	0.3812	0.8384
130	81 - 106	2461.94	832.39	8.22	0.9984	0.1530	0.3572
131	73 - 107	49.45	-35.82	3.18	0.0778	0.0168	0.0355
132	60 - 108	836.44	58.72	8.22	0.5088	0.2205	0.1729
133	100 - 69	3560.38	-1082.55	19.55	0.9106	0.1951	0.3147
134	93 - 109	55.25	-20.24	3.18	0.0869	0.0137	0.0340
135	67 - 110	1072.78	38.99	19.55	0.2744	0.0572	0.0908
136	110 - 111	828.06	-385.25	19.55	0.2118	0.0895	0.0777
137	101 - 60	411.96	-93.44	8.22	0.2506	0.1034	0.0868
138	81 - 112	481.51	-65.31	8.22	0.2929	0.1019	0.1002
139	34 - 113	50.79	-0.61	3.18	0.0799	0.0071	0.0293

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
140	24 - 114	1298.43	-64.03	19.55	0.3321	0.1072	0.1075
141	77 - 79	856.65	-66.44	8.22	0.3474	0.0707	0.1186
142	85 - 115	974.24	-151.18	19.55	0.2492	0.0726	0.0815
143	111 - 116	242.63	-17.15	8.22	0.1476	0.0213	0.0515
144	104 - 117	1918.68	298.35	19.55	0.4907	0.1360	0.1628
145	62 - 48	4045.44	-2764.32	19.55	1.0346	0.1034	0.4146
146	21 - 118	264.46	-11.96	8.22	0.1609	0.0303	0.0548
147	106 - 119	2094.49	-936.60	8.22	0.5096	0.2013	0.1942
148	108 - 120	251.76	20.01	3.18	0.3958	0.0610	0.1493
149	20 - 118	1203.62	-166.17	8.22	0.2440	0.1122	0.0830
150	114 - 121	85.33	14.65	8.22	0.0519	0.0020	0.0180
151	43 - 122	935.52	-393.02	19.55	0.2393	0.1039	0.0844
152	24 - 123	5170.21	1347.73	19.55	0.6612	0.1341	0.2210
153	64 - 103	2536.41	32.29	8.22	1.5428	0.4457	0.5230
154	75 - 124	255.58	-7.40	8.22	0.1555	0.0247	0.0531
155	114 - 125	1056.79	-536.55	19.55	0.2703	0.1513	0.0989
156	62 - 126	47.62	-2.36	8.22	0.0290	0.0009	0.0101
157	75 - 44	10882.45	2995.51	19.55	2.7832	0.0715	0.9399
158	59 - 127	925.73	-406.43	19.55	0.2368	0.1014	0.0831
159	9 - 128	90.36	-17.56	8.22	0.0550	0.0047	0.0190
160	97 - 129	552.47	281.03	8.22	0.3361	0.0149	0.1289
161	39 - 16	2344.60	-702.22	19.55	0.5996	0.1216	0.2039
162	92 - 130	515.93	97.77	3.18	0.8112	0.0877	0.3027

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
163	119 - 131	1797.27	-20.59	8.22	0.4373	0.1921	0.1482
164	84 - 132	4032.18	1339.71	19.55	1.0312	0.0471	0.3515
165	13 - 105	1289.27	-594.49	19.55	0.3297	0.0763	0.1177
166	100 - 133	2008.08	-281.47	19.55	0.5136	0.4229	0.1715
167	108 - 134	447.15	-172.46	8.22	0.2720	0.1403	0.1013
168	85 - 135	678.92	-480.61	19.55	0.1736	0.0724	0.0687
169	103 - 66	306.74	-11.98	4.05	0.3787	0.0816	0.1228
170	44 - 136	1122.83	-357.66	19.55	0.2872	0.1370	0.0991
171	62 - 137	3067.27	376.72	19.55	0.5230	0.2031	0.1743
172	9 - 138	548.10	-260.72	19.55	0.1402	0.0364	0.0502
173	105 - 68	358.48	-178.87	9.65	0.1857	0.1148	0.0796
174	33 - 139	1572.04	-767.30	19.55	0.4021	0.3460	0.1451
175	5 - 140	438.88	139.32	8.22	0.2670	0.0244	0.0940
176	118 - 141	1317.65	192.50	8.22	0.5343	0.1796	0.1831
177	95 - 93	622.25	-73.78	4.05	0.7682	0.2678	0.2504
178	117 - 142	1552.72	276.11	19.55	0.3971	0.0715	0.1345
179	51 - 143	640.36	-409.86	19.55	0.1638	0.0594	0.0625
180	51 - 144	395.73	124.49	8.22	0.2407	0.0064	0.0850
181	61 - 79	210.74	-137.59	8.22	0.1282	0.0469	0.0519
182	53 - 145	50.76	-27.08	3.18	0.0798	0.0154	0.0332
183	80 - 146	1990.91	676.75	8.22	1.2110	0.0607	0.4336
184	50 - 147	935.96	-13.40	19.55	0.2394	0.0472	0.0773
185	18 - 74	945.38	-512.55	19.55	0.2418	0.1467	0.0890

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
186	69 - 148	4649.65	-222.04	19.55	0.4757	0.2568	0.1538
187	85 - 149	1123.70	45.34	19.55	0.2874	0.0591	0.0929
188	134 - 150	156.54	-1.15	3.18	0.2461	0.0089	0.0927
189	75 - 136	3632.13	316.61	19.55	0.9289	0.2096	0.3036
190	45 - 151	151.26	-110.68	8.22	0.0920	0.0334	0.0387
191	52 - 152	1558.71	-351.36	19.55	0.3986	0.2539	0.1355
192	150 - 153	134.81	-97.36	3.18	0.2120	0.1271	0.0960
193	31 - 115	943.30	-496.31	19.55	0.2413	0.1483	0.0882
194	79 - 154	462.51	-333.29	8.22	0.2813	0.1936	0.1150
195	94 - 155	797.26	-575.53	19.55	0.2039	0.1013	0.0810
196	130 - 156	323.84	-33.63	4.05	0.3998	0.2090	0.1301
197	127 - 146	635.74	-216.18	8.22	0.1934	0.0975	0.0687
198	124 - 157	78.46	14.59	3.18	0.1234	0.0113	0.0461
199	126 - 158	41.40	-5.95	3.18	0.0651	0.0064	0.0250
200	118 - 159	81.73	-42.63	3.18	0.1285	0.0417	0.0532
201	74 - 45	1423.59	-143.65	19.55	0.3641	0.0198	0.1185
202	156 - 160	195.09	-133.52	4.05	0.2408	0.1584	0.0961
203	44 - 161	5042.67	1254.82	19.55	0.6448	0.1584	0.2184
204	104 - 162	643.94	-448.82	19.55	0.1647	0.0662	0.0658
205	15 - 85	1781.04	-497.12	19.55	0.4555	0.2763	0.1530
206	152 - 163	633.24	-445.69	19.55	0.1620	0.0675	0.0664
207	134 - 164	114.35	-77.00	3.18	0.1798	0.1037	0.0816
208	82 - 165	52.73	-7.60	3.18	0.0829	0.0082	0.0302

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
209	15 - 34	501.11	-36.36	8.22	0.3048	0.0764	0.1036
210	101 - 166	108.09	-61.59	8.22	0.0657	0.0134	0.0256
211	108 - 167	111.61	-13.28	3.18	0.1755	0.0115	0.0665
212	41 - 168	6123.22	38.17	19.55	0.4474	0.2070	0.1484
213	5 - 97	1441.96	11.43	19.55	0.3688	0.1548	0.1181
214	156 - 169	102.96	-74.10	3.18	0.1619	0.0753	0.0744
215	102 - 170	952.75	51.24	19.55	0.2437	0.0438	0.0826
216	34 - 171	76.98	-56.21	3.18	0.1210	0.0440	0.0550
217	140 - 129	4614.66	352.86	8.22	1.8713	0.7888	0.6362
218	5 - 172	834.54	-259.89	19.55	0.2134	0.0677	0.0716
219	96 - 173	350.75	-166.04	8.22	0.2134	0.0887	0.0800
220	63 - 174	85.88	-24.51	3.18	0.1350	0.0376	0.0525
221	13 - 149	1441.39	-344.68	19.55	0.3686	0.1706	0.1229
222	21 - 175	895.06	-399.30	19.55	0.2289	0.0974	0.0813
223	132 - 176	565.77	-189.81	19.55	0.1447	0.0326	0.0497
224	34 - 177	383.41	-50.89	8.22	0.2332	0.0619	0.0798
225	83 - 157	254.81	42.58	4.05	0.3146	0.0578	0.1032
226	173 - 178	292.63	50.62	3.18	0.4601	0.0784	0.1712
227	104 - 179	439.83	145.42	8.22	0.2675	0.0126	0.0968
228	72 - 180	3146.73	-543.03	19.55	0.5365	0.5040	0.1793
229	142 - 130	6168.62	1052.11	4.05	1.3847	0.0878	0.4735
230	121 - 181	61.94	-25.90	3.18	0.0974	0.0019	0.0405
231	63 - 182	113.50	-82.96	3.18	0.1785	0.1047	0.0827

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
232	125 - 183	594.89	-61.99	19.55	0.1521	0.0235	0.0497
233	105 - 171	1371.01	19.65	4.05	0.6770	0.0536	0.2175
234	149 - 184	908.93	179.33	19.55	0.2325	0.0173	0.0770
235	129 - 185	3560.71	-572.82	8.22	0.4332	0.2650	0.1487
236	75 - 186	1171.28	-120.83	19.55	0.2996	0.0975	0.0981
237	67 - 124	592.23	-231.05	8.22	0.2402	0.1415	0.0894
238	104 - 187	193.93	-56.51	8.22	0.1180	0.0268	0.0422
239	124 - 188	141.96	-7.03	3.18	0.2232	0.0410	0.0820
240	21 - 189	635.96	-467.29	19.55	0.1627	0.0655	0.0655
241	35 - 50	1417.21	-504.98	19.55	0.3625	0.2069	0.1244
242	41 - 190	3066.13	-230.29	19.55	0.3921	0.1814	0.1304
243	153 - 191	112.22	8.53	3.18	0.1764	0.0208	0.0646
244	188 - 192	124.43	-11.66	3.18	0.1956	0.0436	0.0721
245	138 - 32	437.98	-83.40	9.65	0.2269	0.0846	0.0892
246	141 - 193	835.04	-88.58	9.65	0.4327	0.2754	0.1720
247	53 - 194	69.76	-32.35	3.18	0.1097	0.0280	0.0444
248	135 - 195	592.73	-151.70	19.55	0.1516	0.0307	0.0503
249	31 - 184	960.37	-440.06	19.55	0.2456	0.1517	0.0874
250	152 - 196	370.54	52.73	8.22	0.2254	0.0312	0.0800
251	165 - 197	42.96	-30.84	3.18	0.0676	0.0120	0.0300
252	144 - 198	132.12	-67.63	3.18	0.2077	0.1367	0.0856
253	86 - 136	769.07	-493.91	19.55	0.1967	0.1101	0.0772
254	128 - 199	74.29	-50.74	3.18	0.1168	0.0402	0.0524

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{maxstab}}$	$\frac{I_{flow}}{I_{max}}$
255	168 - 200	2681.94	790.94	19.55	0.6859	0.1097	0.2420
256	148 - 201	3822.12	-1059.02	19.55	0.6517	0.6274	0.2230
257	186 - 41	5679.68	676.35	19.55	1.4526	0.1950	0.4794
258	146 - 202	1635.10	173.06	8.22	0.4973	0.1847	0.1712
259	124 - 203	376.78	-273.09	8.22	0.2292	0.1344	0.0960
260	41 - 204	4265.77	-317.12	19.55	0.4364	0.2381	0.1451
261	27 - 50	889.92	-557.92	19.55	0.2276	0.1555	0.0864
262	144 - 205	122.49	-69.44	3.18	0.1926	0.1261	0.0813
263	148 - 206	448.48	-336.03	19.55	0.1147	0.0337	0.0473
264	135 - 207	62.85	-43.87	8.22	0.0382	0.0054	0.0157
265	78 - 174	202.85	-21.52	4.05	0.2504	0.0754	0.0828
266	168 - 208	2494.30	730.38	19.55	0.6379	0.0802	0.2250
267	84 - 209	413.71	-310.14	19.55	0.1058	0.0276	0.0428
268	40 - 210	643.75	-146.53	19.55	0.1646	0.0334	0.0533
269	166 - 108	2262.09	297.92	8.22	1.3760	0.4097	0.4705
270	203 - 211	135.09	-65.46	3.18	0.2124	0.1425	0.0859
271	96 - 212	91.35	-8.77	3.18	0.1436	0.0315	0.0530
272	27 - 213	1496.68	71.45	19.55	0.3828	0.1093	0.1232
273	92 - 202	1883.99	367.17	8.22	1.1460	0.3412	0.3953
274	116 - 214	98.03	4.02	3.18	0.1541	0.0040	0.0566
275	61 - 215	55.38	-25.47	8.22	0.0337	0.0023	0.0126
276	186 - 216	1049.01	-50.30	19.55	0.2683	0.0697	0.0880
277	154 - 109	496.89	169.48	4.05	0.3067	0.0146	0.1014

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
278	152 - 217	417.60	-93.98	19.55	0.1068	0.0156	0.0367
279	17 - 218	3239.29	467.82	19.55	0.5523	0.1956	0.1805
280	40 - 219	168.55	-70.95	8.22	0.1025	0.0299	0.0368
281	37 - 57	3252.07	35.32	19.55	0.8317	0.2328	0.2673
282	198 - 220	76.46	-51.88	3.18	0.1202	0.0381	0.0533
283	169 - 221	65.73	-46.73	3.18	0.1034	0.0298	0.0472
284	114 - 222	101.45	-23.67	8.22	0.0617	0.0065	0.0217
285	47 - 120	286.13	-65.92	4.05	0.3532	0.2226	0.1173
286	187 - 223	115.79	-45.05	3.18	0.1821	0.0788	0.0717
287	72 - 224	3472.02	-1073.13	19.55	0.5920	0.5063	0.2040
288	154 - 225	675.69	-104.87	8.22	0.4110	0.2108	0.1362
289	87 - 156	128.14	-55.75	4.05	0.1582	0.0371	0.0582
290	167 - 226	79.58	-29.37	3.18	0.1251	0.0287	0.0490
291	220 - 227	57.01	-16.52	3.18	0.0896	0.0129	0.0342
292	209 - 228	348.09	54.31	8.22	0.2117	0.0281	0.0725
293	127 - 117	8036.91	1771.56	19.55	1.3703	0.4031	0.4505
294	100 - 229	780.22	-558.46	19.55	0.1995	0.1020	0.0811
295	227 - 230	46.61	-9.56	3.18	0.0733	0.0074	0.0274
296	140 - 231	593.36	-84.71	8.22	0.3609	0.1660	0.1236
297	125 - 121	338.32	183.43	8.22	0.1029	0.0033	0.0399
298	147 - 232	751.22	-212.01	19.55	0.1921	0.0532	0.0647
299	148 - 233	173.30	-105.92	8.22	0.1054	0.0367	0.0427
300	130 - 234	1809.13	-520.29	4.05	0.6381	0.6875	0.2149

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{maxstab}}$	$\frac{I_{flow}}{I_{max}}$
301	110 - 157	1471.99	273.64	4.05	0.7269	0.1543	0.2461
302	136 - 235	1829.17	-501.00	19.55	0.4678	0.4026	0.1599
303	51 - 236	155.11	-100.78	8.22	0.0943	0.0325	0.0379
304	202 - 237	1531.87	-409.92	8.22	0.3727	0.2428	0.1351
305	189 - 162	14300.29	1659.80	19.55	2.4382	0.5989	0.7925
306	184 - 238	1483.43	-487.40	19.55	0.3794	0.2520	0.1301
307	203 - 239	195.04	-4.21	3.18	0.3067	0.0985	0.1116
308	51 - 240	45.25	-33.42	8.22	0.0275	0.0019	0.0115
309	110 - 83	703.56	-119.71	8.22	0.2853	0.0942	0.1009
310	238 - 241	151.36	-12.37	8.22	0.0921	0.0138	0.0317
311	218 - 242	908.89	-378.71	19.55	0.2325	0.1016	0.0835
312	224 - 243	2638.40	209.18	19.55	0.4499	0.1478	0.1460
313	65 - 219	696.52	-46.80	8.22	0.2824	0.0849	0.0954
314	87 - 244	493.56	-217.82	8.22	0.3002	0.1931	0.1160
315	119 - 245	96.88	-57.51	3.18	0.1523	0.0799	0.0650
316	237 - 246	992.62	-607.82	8.22	0.6038	0.1780	0.2502
317	58 - 152	787.53	-332.57	19.55	0.2014	0.0915	0.0731
318	131 - 247	1366.40	412.09	9.65	0.7080	0.0879	0.2908
319	217 - 248	187.34	-38.70	8.22	0.1140	0.0155	0.0409
320	238 - 249	1161.73	234.50	19.55	0.2971	0.0289	0.0992
321	103 - 130	584.48	-6.48	4.05	0.4811	0.2149	0.1558
322	51 - 250	103.85	5.98	8.22	0.0632	0.0011	0.0213
323	222 - 251	67.31	-49.62	3.18	0.1058	0.0347	0.0491

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
324	117 - 252	6206.50	-2598.41	19.55	1.5873	0.1632	0.5740
325	39 - 242	2004.04	-66.82	19.55	0.5125	0.2459	0.1671
326	198 - 253	44.59	-10.21	3.18	0.0701	0.0071	0.0264
327	139 - 254	1170.09	371.07	19.55	0.2993	0.0026	0.1010
328	246 - 255	270.42	-79.53	8.22	0.1645	0.0402	0.0581
329	21 - 148	5030.99	412.39	19.55	1.2867	0.6358	0.4189
330	140 - 256	187.48	-14.07	3.18	0.2948	0.1024	0.1085
331	212 - 257	77.09	-52.25	3.18	0.1212	0.0404	0.0548
332	237 - 258	92.22	-20.65	3.18	0.1450	0.0019	0.0569
333	6 - 97	1603.95	63.85	19.55	0.4102	0.1406	0.1320
334	254 - 259	847.96	-382.88	19.55	0.2169	0.0861	0.0766
335	245 - 260	82.56	12.10	3.18	0.1298	0.0081	0.0482
336	255 - 261	202.55	19.02	3.18	0.3185	0.0324	0.1175
337	166 - 164	989.47	83.32	4.05	0.6108	0.1993	0.1984
338	231 - 262	176.34	-6.67	3.18	0.2773	0.0582	0.1029
339	129 - 263	867.50	-9.00	9.65	0.4495	0.2233	0.1737
340	224 - 264	433.44	-96.41	19.55	0.1109	0.0155	0.0367
341	75 - 216	1801.88	-13.99	19.55	0.4608	0.1672	0.1501
342	129 - 265	49.53	8.51	3.18	0.0779	0.0038	0.0290
343	115 - 266	1422.74	162.71	19.55	0.3639	0.0759	0.1188
344	266 - 267	927.90	273.42	19.55	0.2373	0.0047	0.0810
345	11 - 128	360.65	-66.76	8.22	0.2194	0.0757	0.0755
346	111 - 268	194.13	-0.03	8.22	0.1181	0.0045	0.0411

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
347	72 - 269	381.35	-115.12	19.55	0.0975	0.0142	0.0335
348	144 - 270	64.87	-39.53	3.18	0.1020	0.0277	0.0438
349	182 - 160	1691.72	1124.74	4.05	2.0885	0.1257	0.7913
350	201 - 271	617.50	-249.78	19.55	0.1579	0.0424	0.0551
351	242 - 272	797.62	-593.79	19.55	0.2040	0.1101	0.0843
352	152 - 273	530.42	-226.29	19.55	0.1357	0.0345	0.0494
353	49 - 145	314.75	-33.68	4.05	0.3886	0.0911	0.1272
354	44 - 274	1240.59	-449.37	19.55	0.3173	0.1802	0.1109
355	117 - 275	1362.67	113.48	19.55	0.3485	0.0846	0.1167
356	156 - 276	121.24	-85.82	3.18	0.1906	0.1043	0.0872
357	134 - 153	642.77	-28.56	4.05	0.5290	0.1140	0.1759
358	97 - 277	1881.19	154.43	19.55	0.4811	0.1800	0.1574
359	178 - 278	185.93	39.19	3.18	0.2923	0.0287	0.1096
360	178 - 279	50.72	7.86	3.18	0.0797	0.0029	0.0296
361	276 - 234	2436.13	-216.29	4.05	3.0076	0.3907	0.9897
362	128 - 280	327.01	-223.97	8.22	0.1989	0.0985	0.0825
363	72 - 281	2724.15	8.83	19.55	0.4645	0.2229	0.1529
364	133 - 282	1787.38	-1314.35	19.55	0.4571	0.1867	0.1930
365	112 - 187	1662.57	-84.91	8.22	1.0113	0.8788	0.3455
366	269 - 283	115.39	-84.99	8.22	0.0702	0.0143	0.0301
367	136 - 284	1896.43	308.05	19.55	0.4850	0.1288	0.1620
368	85 - 285	178.81	-92.18	8.22	0.1088	0.0362	0.0414
369	141 - 159	74.24	-54.33	4.05	0.0917	0.0076	0.0376

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
370	95 - 286	113.91	-35.03	3.18	0.1791	0.0546	0.0688
371	264 - 287	195.61	-16.42	8.22	0.1190	0.0154	0.0405
372	97 - 288	1214.93	217.79	19.55	0.3107	0.0373	0.1029
373	215 - 71	534.76	-90.94	8.22	0.3253	0.1275	0.1112
374	229 - 289	539.73	-378.94	19.55	0.1380	0.0465	0.0553
375	233 - 290	136.07	-14.86	3.18	0.2139	0.0841	0.0790
376	69 - 291	656.53	-144.81	19.55	0.1679	0.0360	0.0555
377	1 - 216	11115.80	1780.18	19.55	2.8429	0.3167	0.9312
378	239 - 292	118.63	-19.22	3.18	0.1865	0.0459	0.0694
379	263 - 293	519.40	-167.77	8.22	0.3159	0.1779	0.1151
380	279 - 294	43.36	-31.48	3.18	0.0682	0.0127	0.0309
381	267 - 199	250.58	-102.08	4.05	0.3094	0.2072	0.1095
382	285 - 295	54.91	-34.13	3.18	0.0863	0.0198	0.0373
383	284 - 296	1412.97	338.08	19.55	0.3614	0.0341	0.1246
384	129 - 297	129.16	-83.37	3.18	0.2031	0.1580	0.0887
385	98 - 145	55.90	-31.62	4.05	0.0690	0.0055	0.0259
386	17 - 298	1037.13	-221.62	19.55	0.2653	0.0932	0.0877
387	262 - 299	95.96	3.24	3.18	0.1509	0.0178	0.0554
388	130 - 300	1922.11	248.16	4.05	0.5273	0.2022	0.1721
389	77 - 35	2622.34	-387.30	19.55	0.6707	0.2337	0.2202
390	293 - 301	128.12	-29.31	3.18	0.2014	0.0462	0.0779
391	297 - 302	111.42	-63.54	3.18	0.1752	0.0735	0.0740
392	252 - 303	768.67	214.82	19.55	0.1966	0.0045	0.0660

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
393	162 - 233	803.50	-30.20	8.22	0.3258	0.0701	0.1115
394	233 - 304	403.75	43.06	8.22	0.2456	0.0333	0.0837
395	277 - 305	1264.84	395.40	19.55	0.3235	0.0046	0.1128
396	145 - 306	208.61	-26.92	4.05	0.2575	0.0800	0.0834
397	268 - 214	238.34	-53.53	4.05	0.2942	0.1399	0.0976
398	244 - 307	233.28	14.58	3.18	0.3668	0.0156	0.1405
399	72 - 308	1978.94	241.99	19.55	0.5061	0.1807	0.1679
400	130 - 309	2461.23	-788.84	4.05	0.6077	0.6774	0.2066
401	151 - 285	1817.07	-36.66	8.22	1.1053	0.6605	0.3747
402	237 - 310	354.12	-4.60	8.22	0.2154	0.0425	0.0761
403	285 - 311	293.71	-152.39	8.22	0.1787	0.0648	0.0682
404	282 - 312	816.21	-602.72	19.55	0.2087	0.1091	0.0839
405	162 - 223	768.55	22.35	4.05	0.4744	0.2029	0.1550
406	248 - 313	121.56	3.25	3.18	0.1911	0.0514	0.0702
407	291 - 314	201.89	-12.00	8.22	0.1228	0.0152	0.0417
408	300 - 315	1504.32	100.83	4.05	0.4643	0.2030	0.1546
409	102 - 273	721.88	-533.47	19.55	0.1846	0.0775	0.0777
410	71 - 316	159.81	-10.16	3.18	0.2513	0.0618	0.0924
411	311 - 317	241.02	42.68	3.18	0.3790	0.0112	0.1411
412	281 - 318	1860.08	-693.29	19.55	0.3171	0.1933	0.1139
413	122 - 79	398.37	-139.38	9.65	0.2064	0.0730	0.0849
414	264 - 319	191.47	-30.08	8.22	0.1165	0.0192	0.0400
415	267 - 320	610.07	-428.65	19.55	0.1560	0.0595	0.0625

Table A.20: Load-flow solution for 330-bus and 430-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
416	97 - 321	601.81	-386.79	19.55	0.1539	0.0541	0.0597
417	39 - 177	592.24	-177.79	8.22	0.2402	0.1267	0.0856
418	140 - 322	500.39	-212.98	8.22	0.3044	0.1786	0.1121
419	119 - 323	100.38	0.46	3.18	0.1578	0.0331	0.0579
420	242 - 324	309.64	13.59	8.22	0.1883	0.0289	0.0655
421	163 - 248	1302.18	-53.22	8.22	0.3960	0.0514	0.1386
422	152 - 325	190.92	-88.03	8.22	0.1161	0.0366	0.0449
423	322 - 326	407.60	-2.36	8.22	0.2479	0.0512	0.0840
424	34 - 327	47.89	10.91	3.18	0.0753	0.0027	0.0283
425	127 - 291	1159.98	-102.54	19.55	0.2967	0.0974	0.0956
426	192 - 328	72.54	-21.15	3.18	0.1140	0.0213	0.0438
427	242 - 329	258.61	-23.50	8.22	0.1573	0.0297	0.0548
428	108 - 330	1187.42	-427.38	9.65	0.6152	0.5998	0.2589
429	288 - 305	1767.60	142.25	19.55	0.4521	0.1472	0.1486
430	105 - 327	189.79	-33.50	4.05	0.2343	0.1091	0.0764

A.5 A 82 bus Network with 121 lines - Tie-Line Interconnection Example

Finally, in addition to previous example networks which were developed through radial and loop expansion of the initial network, an example of interconnecting two previously generated networks through tie-line connections, is presented. Both interconnected networks were developed from a 6-node core network. The first was a 46 bus and 66 line network, while the second was 36 bus and 51 line network. The two given networks were interconnected through four tie-line connections, to form a larger power system network, of 82 buses and 121 lines.

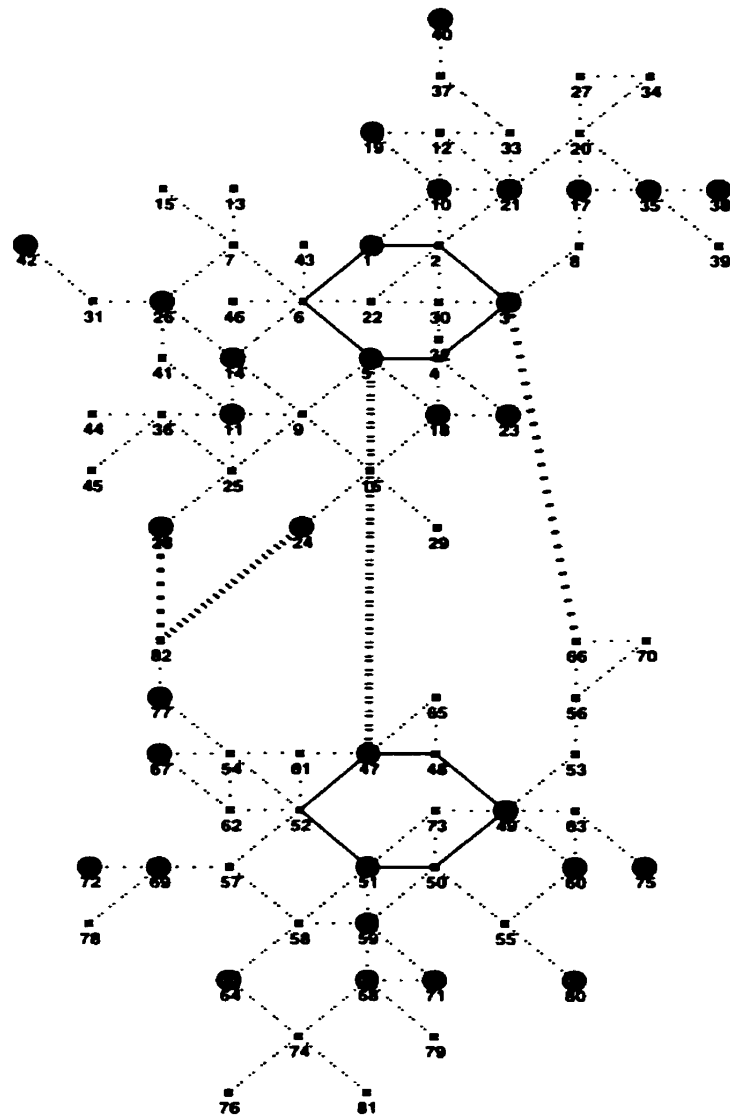


Figure A.11: An interconnection of two previously developed networks into the larger power system through tie-line connections - network layout.

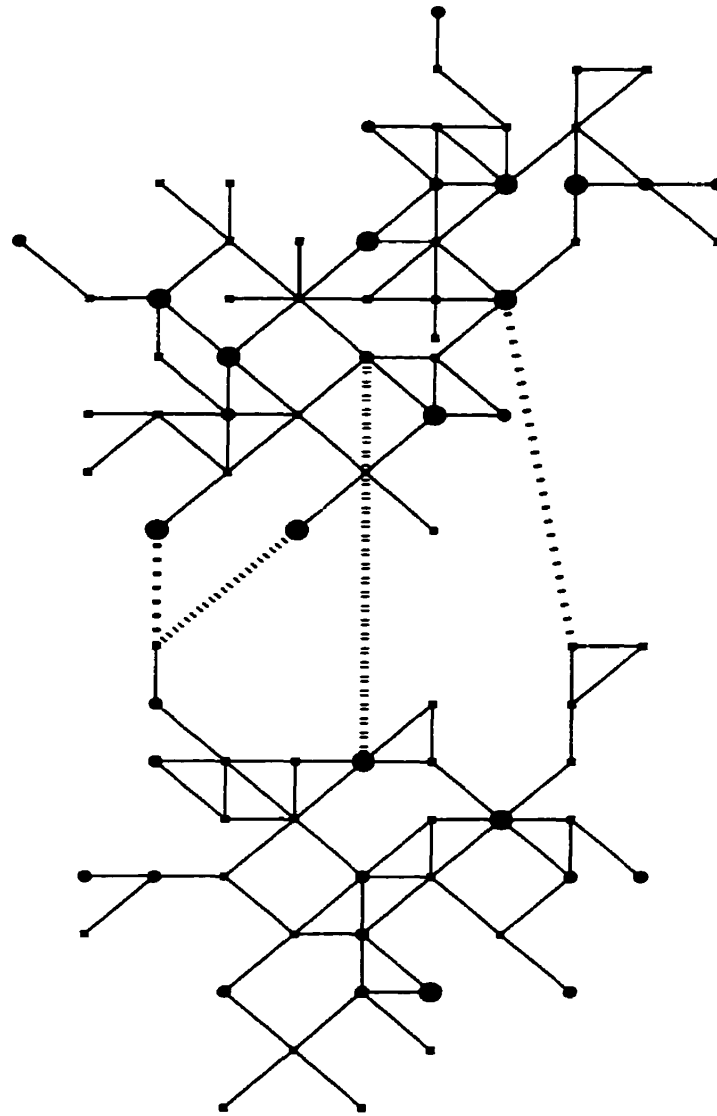


Figure A.12: An interconnection of two previously developed networks into the larger power system through tie-line connections - topology layout.

Line Data

Table A.21: Line data for network of 82 buses and 121 lines.

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the Line (km)
				R (Ω)	X (Ω)	B (mS)			
1	1 - 2	735	3	0.2467	6.8907	0.8117	0.00	14.24	59
2	2 - 3	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
3	3 - 4	735	10	0.1600	4.4697	5.8501	0.00	47.48	128
4	4 - 5	735	10	0.2000	5.5871	7.3126	0.00	47.48	160
5	5 - 6	735	5	0.2600	7.2632	2.3766	0.00	23.74	104
6	6 - 1	735	9	0.1556	4.3455	4.6070	0.00	42.73	112
7	6 - 7	735	2	1.0938	30.5543	1.5996	0.00	9.50	175
8	3 - 8	735	4	0.7906	22.0864	4.6252	0.00	18.99	253
9	5 - 9	735	4	0.4156	11.6107	2.4315	0.00	18.99	133
10	2 - 10	500	2	1.0120	21.0268	0.9083	375.00	5.60	109
11	1 - 10	500	2	1.0145	11.9657	0.7124	93.75	5.77	73
12	9 - 11	735	2	0.6125	17.1104	0.8958	0.00	9.50	98
13	10 - 12	500	2	0.8743	18.1665	0.7847	0.00	5.60	94
14	7 - 13	500	2	0.2604	5.4113	0.2338	375.00	5.60	28
15	6 - 14	735	2	0.2250	6.2855	0.3291	0.00	9.50	36
16	14 - 9	735	2	0.9000	25.1419	1.3163	0.00	9.50	144
17	7 - 15	735	2	0.7312	20.4278	1.0695	0.00	9.50	117
18	9 - 16	735	2	0.9562	26.7132	1.3985	0.00	9.50	153
19	14 - 11	735	2	1.0187	28.4592	1.4900	0.00	9.50	163
20	8 - 17	735	2	0.7500	20.9516	1.0969	0.00	9.50	120

Table A.21: Line data for network of 82 buses and 121 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
21	5 - 18	735	2	1.2562	35.0939	1.8373	0.00	9.50	201
22	4 - 18	735	2	1.9875	55.5216	2.9068	0.00	9.50	318
23	18 - 16	735	2	0.4438	12.3963	0.6490	0.00	9.50	71
24	10 - 19	345	2	0.2939	3.0930	0.0881	179.00	2.90	13
25	17 - 20	735	2	0.4000	11.1742	0.5850	0.00	9.50	64
26	2 - 21	735	2	0.2062	5.7617	0.3016	0.00	9.50	33
27	2 - 22	735	2	0.2062	5.7617	0.3016	0.00	9.50	33
28	21 - 10	500	2	0.8929	18.5530	0.8014	125.00	5.60	96
29	12 - 19	345	2	1.6266	19.9445	0.9256	59.67	4.19	107
30	21 - 12	500	2	1.3394	27.8296	1.2022	125.00	5.60	144
31	4 - 23	500	2	0.5488	11.4024	0.4926	375.00	5.60	59
32	16 - 24	735	2	0.6562	18.3326	0.9598	0.00	9.50	105
33	22 - 6	735	2	1.1625	32.4749	1.7002	0.00	9.50	186
34	9 - 25	500	2	0.9301	19.3261	0.8348	375.00	5.60	100
35	14 - 26	735	2	0.3750	10.4758	0.5484	0.00	9.50	60
36	18 - 23	500	2	3.0297	35.7330	2.1273	187.50	5.77	218
37	20 - 27	735	2	0.9875	27.5862	1.4442	0.00	9.50	158
38	25 - 28	345	2	1.5600	16.4164	0.4674	179.00	2.90	69
39	21 - 20	735	2	1.2938	36.1414	1.8921	0.00	9.50	207
40	16 - 29	735	2	1.2312	34.3955	1.8007	0.00	9.50	197
41	2 - 30	500	2	0.5209	10.8226	0.4675	375.00	5.60	56
42	11 - 25	500	4	0.1535	3.1888	0.5510	53.57	11.20	33

Table A.21: Line data for network of 82 buses and 121 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
43	26 - 31	500	2	0.4837	10.0496	0.4341	375.00	5.60	52
44	30 - 32	345	2	1.9896	20.9369	0.5961	179.00	2.90	88
45	3 - 30	500	2	2.3348	27.5374	1.6394	187.50	5.77	168
46	21 - 33	735	2	0.6000	16.7612	0.8775	0.00	9.50	96
47	20 - 34	735	2	1.0438	29.1576	1.5265	0.00	9.50	167
48	33 - 12	500	2	0.8836	18.3598	0.7931	125.00	5.60	95
49	20 - 35	735	2	1.5312	42.7761	2.2395	0.00	9.50	245
50	25 - 36	345	2	3.7757	39.7325	1.1312	179.00	2.90	167
51	11 - 36	345	3	2.1384	26.2199	2.7379	89.50	6.28	211
52	33 - 37	735	2	0.4562	12.7455	0.6673	0.00	9.50	73
53	35 - 38	500	2	0.1395	2.8989	0.1252	375.00	5.60	15
54	17 - 35	735	3	0.8000	22.3483	2.6326	0.00	14.24	192
55	35 - 39	735	2	0.3500	9.7774	0.5119	0.00	9.50	56
56	37 - 40	500	2	0.0558	1.1596	0.0501	375.00	5.60	6
57	22 - 30	500	2	1.5068	31.3083	1.3524	187.50	5.60	162
58	11 - 41	735	2	0.4625	12.9201	0.6764	0.00	9.50	74
59	31 - 42	345	2	0.5878	6.1859	0.1761	179.00	2.90	26
60	27 - 34	735	2	0.3241	7.9457	0.3704	0.00	8.70	43
61	6 - 43	735	2	1.5438	43.1253	2.2578	0.00	9.50	247
62	36 - 44	345	2	0.5426	5.7101	0.1626	0.00	2.90	24
63	26 - 41	735	2	1.4875	41.5539	2.1755	0.00	9.50	238
64	36 - 45	345	2	0.9948	10.4684	0.2980	0.00	2.90	44

Table A.21: Line data for network of 82 buses and 121 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
65	6 - 46	735	3	1.0375	28.9830	3.4141	0.00	14.24	249
66	26 - 7	735	2	0.7250	20.2532	1.0603	0.00	9.50	116
67	47 - 48	735	3	0.2467	6.8907	0.8117	0.00	14.24	59
68	48 - 49	735	4	0.2500	6.9839	1.4625	0.00	18.99	80
69	49 - 50	735	10	0.1600	4.4697	5.8501	0.00	47.48	128
70	50 - 51	735	10	0.2000	5.5871	7.3126	0.00	47.48	160
71	51 - 52	735	5	0.2600	7.2632	2.3766	0.00	23.74	104
72	52 - 47	735	9	0.1556	4.3455	4.6070	0.00	42.73	112
73	49 - 53	735	4	0.7781	21.7372	4.5521	0.00	18.99	249
74	52 - 54	735	3	0.3458	9.6610	1.1380	0.00	14.24	83
75	50 - 55	735	2	0.7000	19.5548	1.0238	0.00	9.50	112
76	53 - 56	735	2	0.5938	16.5866	0.8684	0.00	9.50	95
77	52 - 57	735	2	0.4562	12.7455	0.6673	0.00	9.50	73
78	51 - 58	735	2	1.6438	45.9188	2.4040	0.00	9.50	263
79	57 - 58	735	2	1.3125	36.6652	1.9196	0.00	9.50	210
80	50 - 59	500	2	0.0930	1.9326	0.0835	375.00	5.60	10
81	49 - 60	500	2	0.5953	12.3687	0.5343	375.00	5.60	64
82	51 - 59	500	6	0.2480	5.1536	2.0036	53.57	16.80	80
83	55 - 60	500	3	0.2790	5.7978	0.5635	62.50	8.40	45
84	58 - 59	500	5	0.1525	3.1695	0.8557	37.50	14.00	41
85	52 - 61	735	2	0.6125	17.1104	0.8958	0.00	9.50	98
86	52 - 62	500	2	0.5581	11.5957	0.5009	375.00	5.60	60

Table A.21: Line data for network of 82 buses and 121 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
87	47 - 61	735	2	0.8562	23.9197	1.2523	0.00	9.50	137
88	49 - 63	735	2	0.1375	3.8411	0.2011	0.00	9.50	22
89	58 - 64	500	2	0.1953	4.0585	0.1753	375.00	5.60	21
90	61 - 54	735	2	0.3188	8.9044	0.4662	0.00	9.50	51
91	47 - 65	735	2	1.0750	30.0306	1.5722	0.00	9.50	172
92	56 - 66	735	2	0.3750	10.4758	0.5484	0.00	9.50	60
93	63 - 60	500	2	2.2602	46.9624	2.0287	187.50	5.60	243
94	62 - 67	345	2	3.2330	34.0225	0.9686	179.00	2.90	143
95	59 - 68	500	4	1.5301	31.7914	5.4932	0.00	11.20	329
96	54 - 67	345	3	0.8209	10.0655	1.0511	59.67	6.28	81
97	57 - 69	735	2	1.1812	32.9987	1.7276	0.00	9.50	189
98	56 - 70	735	2	0.7312	20.4278	1.0695	0.00	9.50	117
99	48 - 65	735	2	0.9750	27.2370	1.4260	0.00	9.50	156
100	59 - 71	500	2	4.2665	50.3213	2.9958	0.00	5.77	307
101	69 - 72	500	2	0.1395	2.8989	0.1252	375.00	5.60	15
102	71 - 68	500	2	0.1953	4.0585	0.1753	0.00	5.60	21
103	50 - 73	735	2	0.2812	7.8568	0.4113	0.00	9.50	45
104	68 - 74	500	8	0.5488	11.4024	7.8809	0.00	22.40	236
105	54 - 62	500	3	0.2232	4.6383	0.4508	93.75	8.40	36
106	63 - 75	500	2	0.5674	11.7889	0.5092	375.00	5.60	61
107	74 - 76	500	2	1.3580	28.2161	1.2189	0.00	5.60	146
108	66 - 70	735	2	0.4562	12.7455	0.6673	0.00	9.50	73

Table A.21: Line data for network of 82 buses and 121 lines (continued).

Line No	Line term.	Volt. Level (kV)	Num of circ	Line Parameters			X_{tr} (Ω)	I_{max} (kA)	Length of the line (km)
				R (Ω)	X (Ω)	B (mS)			
109	54 - 77	735	4	0.8625	24.0943	5.0457	0.00	18.99	276
110	69 - 78	735	2	0.4062	11.3488	0.5942	0.00	9.50	65
111	74 - 64	500	2	2.7439	57.0120	2.4628	0.00	5.60	295
112	68 - 79	500	2	1.2650	26.2835	1.1354	0.00	5.60	136
113	55 - 80	500	2	0.4558	9.4698	0.4091	375.00	5.60	49
114	49 - 73	735	2	0.4312	12.0471	0.6307	0.00	9.50	69
115	74 - 81	500	2	0.0186	0.3865	0.0167	0.00	5.60	2
116	77 - 82	735	3	1.1583	32.3585	3.8117	0.00	14.24	278
117	73 - 51	735	2	0.8938	24.9673	1.3071	0.00	9.50	143
118	5 - 47	735	2	1.3942	34.1848	1.5937	0.00	8.70	185
119	3 - 66	735	2	0.2788	6.8370	0.3187	0.00	8.70	37
120	28 - 82	345	2	1.4922	15.7027	0.4470	0.00	2.90	66
121	24 - 82	735	2	0.3316	8.1304	0.3790	0.00	8.70	44

Bus Data

Table A.22: Voltage regulated bus data for network of 82 buses and 121 lines.

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MW)	Q_{gmin} (MVA _r)	Q_{gmax} (MVA _r)	P_d (MW)	Q_d (MVA _r)
1	1.0000	13500.00	7034.78	0.00	1057.00	350.54	325.55
3	1.0000	38880.00	38870.04	0.00	5809.00	1057.89	52.89
11	1.0000	0.00	0.00	0.00	1772.00	2497.03	752.26
14	0.9761	3200.00	3192.40	-15.00	40.00	1959.92	1759.44
17	0.9532	4550.00	4543.10	-15.00	40.00	2407.87	2308.70
18	0.9847	3920.00	3915.83	-15.00	40.00	2912.12	484.15
19	1.0000	0.00	0.00	-59.00	98.00	592.09	49.00
21	0.9876	3600.00	3598.17	-15.00	40.00	1133.75	729.24
23	1.0000	0.00	0.00	-50.00	115.00	661.08	277.20
24	0.9579	28250.00	28245.60	-15.00	40.00	1110.59	946.54
26	0.9764	2540.00	2532.40	-15.00	40.00	197.87	1376.53
28	1.0000	1110.00	1102.22	-15.00	40.00	1027.16	324.11
35	1.0000	0.00	0.00	0.00	1686.00	3094.88	154.74
36	1.0218	0.00	0.00	-30.00	50.00	73.53	3.68
38	1.0000	0.00	0.00	0.00	397.00	512.60	168.48
40	1.0000	0.00	0.00	-50.00	185.00	289.42	95.13
42	1.0000	0.00	0.00	-30.00	50.00	79.70	26.19
47	1.0000	15080.00	8838.43	0.00	1453.00	1070.11	991.22
49	1.0000	22660.00	22651.78	0.00	343.00	1152.53	2404.23
59	1.0000	0.00	0.00	-50.00	217.00	1003.67	208.57

Table A.22: Voltage regulated bus data for network of 82 buses and 121 lines (continued).

Bus No	Voltage (p.u.)	Generation				Load	
		P_{gmax} (MW)	P_g (MVA _r)	Q_{gmin} (MVA _r)	Q_{gmax} (MW)	P_d (MW)	Q_d (MVA _r)
60	1.0000	0.00	0.00	-30.00	50.00	1317.74	222.60
61	0.9841	0.00	0.00	-50.00	266.00	381.60	19.08
64	1.0000	0.00	0.00	0.00	486.00	1796.56	191.10
68	1.0000	0.00	0.00	0.00	361.00	185.43	1325.99
69	1.0000	0.00	0.00	0.00	769.00	771.15	616.99
71	1.0000	2540.00	2538.46	-50.00	275.00	2163.37	459.06
72	1.0000	0.00	0.00	-50.00	143.00	268.00	88.09
77	1.0000	0.00	0.00	-56.00	92.00	1138.98	1857.69
80	1.0000	0.00	0.00	-30.00	50.00	178.47	58.66
82	1.0333	0.00	0.00	0.00	12586.00	27247.58	1362.38

Table A.23: Load (PQ) bus data.

Bus No	P_d (MW)	Q_d (MVA _r)
2	113.66	528.05
4	1144.36	1471.95
5	1403.70	5518.52
6	1928.04	4115.62
7	1271.69	775.97
8	1711.24	912.58
9	1696.74	3769.72
10	481.39	160.59
12	821.48	262.44
13	71.41	23.47
15	954.31	313.67
16	2043.05	2068.01
20	321.98	2948.73
22	28.62	946.93
25	742.92	58.14
27	415.20	365.69
29	1285.32	422.47
30	617.29	389.65
31	33.72	52.91
32	73.30	24.09

Table A.23: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
33	88.27	573.54
34	935.35	260.19
37	183.19	104.69
39	1546.77	508.40
41	1903.70	244.54
43	1122.99	369.11
44	465.44	152.98
45	48.06	15.80
46	2446.57	804.15
48	1458.49	1328.97
50	452.99	886.92
51	2894.85	5558.25
52	28.98	906.88
53	604.76	443.46
54	1979.48	4647.95
55	256.60	439.61
56	595.30	966.51
57	386.51	2553.44
58	95.71	527.66
62	293.02	6.74

Table A.23: Load (PQ) Bus Data
(continued)

Bus No	P_d (MW)	Q_d (MVA _r)
63	611.94	602.20
65	3799.04	919.46
66	20197.75	3271.15
67	469.88	6.11
70	1307.07	288.99
73	3221.79	142.72
74	331.12	1031.98
75	82.50	56.73
76	375.16	123.31
78	465.35	152.95
79	650.53	213.82
81	752.92	247.47

Load-Flow Solution

Table A.24: Load-flow solution for the 82-bus and 121-line network.

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
1**	7034.78	1056.54	350.54	325.55	1.0000	0.0000
2	0.00	0.00	113.66	528.05	0.9944	0.0162
3	38870.04	5808.10	1057.89	52.89	1.0000	0.0788
4	0.00	0.00	1144.36	1471.95	1.0010	0.0093
5	0.00	0.00	1403.70	5518.52	0.9800	-0.0541
6	0.00	0.00	1928.04	4115.62	0.9857	-0.0597
7	0.00	0.00	1271.69	775.97	0.9800	-0.1320
8	0.00	0.00	1711.24	912.58	0.9779	-0.0833
9	0.00	0.00	1696.74	3769.72	0.9597	-0.1252
10	0.00	0.00	481.39	160.59	1.0000	-0.2342
11	0.00	1771.71	2497.03	752.26	1.0000	-0.1965
12	0.00	0.00	821.48	262.44	0.9951	-0.2647
13	0.00	0.00	71.41	23.47	0.9808	-0.2453
14	3192.40	0.00	1959.92	1759.44	0.9761	-0.0836
15	0.00	0.00	954.31	313.67	0.9765	-0.1697
16	0.00	0.00	2043.05	2068.01	0.9577	-0.1258
17	4543.10	0.00	2407.87	2308.70	0.9532	-0.1720
18	3915.83	0.00	2912.12	484.15	0.9847	-0.0810
19	0.00	88.56	592.09	49.00	1.0000	-0.5363
20	0.00	0.00	321.98	2948.73	0.9503	-0.1888

**For the load-flow solution, bus number 1, from the first network was selected as a slack and reference bus , for the complete, interconnected, system

Table A.24: Load-flow solution for the 82-bus and 121-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
21	3598.17	0.00	1133.75	729.24	0.9876	-0.0042
22	0.00	0.00	28.62	946.93	0.9901	0.0025
23	0.00	103.76	661.08	277.20	1.0000	-0.4361
24	28245.60	0.00	1110.59	946.54	0.9579	-0.0724
25	0.00	0.00	742.92	58.14	1.0151	-0.3735
26	2532.40	0.00	197.87	1376.53	0.9764	-0.0901
27	0.00	0.00	415.20	365.69	0.9558	-0.2262
28	1102.22	0.00	1027.16	324.11	1.0000	-0.4549
29	0.00	0.00	1285.32	422.47	0.9520	-0.2157
30	0.00	0.00	617.29	389.65	0.9873	-0.2051
31	0.00	0.00	33.72	52.91	0.9838	-0.2731
32	0.00	0.00	73.30	24.09	0.9971	-0.3307
33	0.00	0.00	88.27	573.54	0.9835	-0.0345
34	0.00	0.00	935.35	260.19	0.9566	-0.2301
35	0.00	1685.53	3094.88	154.74	1.0000	-0.3279
36	0.00	41.74	73.53	3.68	1.0218	-0.6342
37	0.00	0.00	183.19	104.69	0.9834	-0.0460
38	0.00	396.48	512.60	168.48	1.0000	-1.2145
39	0.00	0.00	1546.77	508.40	0.9918	-0.3558
40	0.00	167.50	289.42	95.13	1.0000	-0.5048
41	0.00	0.00	1903.70	244.54	1.0012	-0.2070
42	0.00	31.45	79.70	26.19	1.0000	-0.3995

Table A.24: Load-flow solution for the 82-bus and 121-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVA _r)	P_d (MW)	Q_d (MVA _r)		
43	0.00	0.00	1122.99	369.11	0.9973	-0.1517
44	0.00	0.00	465.44	152.98	1.0127	-0.6552
45	0.00	0.00	48.06	15.80	1.0216	-0.6383
46	0.00	0.00	2446.57	804.15	0.9757	-0.1968
47	8838.43	1452.06	1070.11	991.22	1.0000	-0.1031
48	0.00	0.00	1458.49	1328.97	0.9942	-0.0822
49	22651.78	342.04	1152.53	2404.23	1.0000	-0.0139
50	0.00	0.00	452.99	886.92	1.0006	-0.0861
51	0.00	0.00	2894.85	5558.25	0.9800	-0.1487
52	0.00	0.00	28.98	906.88	0.9870	-0.1572
53	0.00	0.00	604.76	443.46	0.9755	-0.1203
54	0.00	0.00	1979.48	4647.95	0.9639	-0.2215
55	0.00	0.00	256.60	439.61	0.9936	-0.1299
56	0.00	0.00	595.30	966.51	0.9338	-0.1856
57	0.00	0.00	386.51	2553.44	0.9626	-0.2276
58	0.00	0.00	95.71	527.66	0.9704	-0.2977
59	0.00	196.92	1003.67	208.57	1.0000	-0.6348
60	0.00	37.12	1317.74	222.60	1.0000	-0.3439
61	0.00	241.04	381.60	19.08	0.9841	-0.1836
62	0.00	0.00	293.02	6.74	1.0118	-0.3271
63	0.00	0.00	611.94	602.20	0.9977	-0.0212
64	0.00	485.13	1796.56	191.10	1.0000	-1.3224

Table A.24: Load-flow solution for the 82-bus and 121-line network (continued).

Bus No	Generation		Load		Voltage magnitude (p.u.)	δ (rad)
	P_g (MW)	Q_g (MVAr)	P_d (MW)	Q_d (MVAr)		
65	0.00	0.00	3799.04	919.46	0.9844	-0.1946
66	0.00	0.00	20197.75	3271.15	0.9211	-0.2001
67	0.00	0.00	469.88	6.11	1.0000	-0.4636
68	0.00	360.14	185.43	1325.99	1.0000	-0.9004
69	0.00	768.73	771.15	616.99	1.0000	-0.3249
70	0.00	0.00	1307.07	288.99	0.9268	-0.2167
71	2538.46	249.64	2163.37	459.06	1.0000	-0.8754
72	0.00	129.25	268.00	88.09	1.0000	-0.7420
73	0.00	0.00	3221.79	142.72	0.9985	-0.0960
74	0.00	0.00	331.12	1031.98	0.9891	-1.0267
75	0.00	0.00	82.50	56.73	1.0000	-0.1495
76	0.00	0.00	375.16	123.31	0.9890	-1.0701
77	0.00	83.06	1138.98	1857.69	1.0000	-0.3637
78	0.00	0.00	465.35	152.95	0.9998	-0.3347
79	0.00	0.00	650.53	213.82	0.9862	-0.9694
80	0.00	37.05	178.47	58.66	1.0000	-0.4098
81	0.00	0.00	752.92	247.47	0.9886	-1.0278
82	0.00	12585.60	27247.58	1362.38	1.0333	-0.4741

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows.

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max_{stab}}}$	$\frac{I_{flow}}{I_{max}}$
1	1 - 2	-1242.20	272.87	19.55	-0.2118	-0.0358	0.0701
2	2 - 3	-4819.26	-496.49	19.55	-0.6163	-0.1408	0.2015
3	3 - 4	8398.92	-1704.39	19.55	0.4296	0.1571	0.1418
4	4 - 5	6084.18	22.32	19.55	0.3112	0.1422	0.1006
5	5 - 6	385.84	-1044.66	19.55	0.0395	0.0117	0.0376
6	6 - 1	-7360.45	-2479.44	19.55	-0.4183	-0.1338	0.1448
7	6 - 7	1237.58	-319.33	19.55	0.3165	0.1582	0.1073
8	3 - 8	3886.56	-535.22	19.55	0.4970	0.3531	0.1623
9	5 - 9	3138.71	292.82	19.55	0.4014	0.1525	0.1330
10	2 - 10	155.59	-96.60	8.22	0.0946	0.0304	0.0380
11	1 - 10	549.45	-29.74	9.65	0.2847	0.0662	0.1102
12	9 - 11	2114.51	-1442.68	19.55	0.5408	0.1514	0.2206
13	10 - 12	419.56	-44.53	8.22	0.2552	0.0707	0.0870
14	7 - 13	71.42	-24.59	8.22	0.0434	0.0036	0.0159
15	6 - 14	2005.26	681.62	19.55	0.5129	0.0527	0.1777
16	14 - 9	847.40	-8.48	19.55	0.2167	0.0891	0.0718
17	7 - 15	955.61	-203.00	19.55	0.2444	0.0817	0.0825
18	9 - 16	13.05	-309.58	19.55	0.0033	0.0015	0.0267
19	14 - 11	2071.46	-783.24	19.55	0.5298	0.2466	0.1877
20	8 - 17	2152.47	357.95	19.55	0.5505	0.1887	0.1846
21	5 - 18	395.62	-556.78	19.55	0.1012	0.0575	0.0577
22	4 - 18	870.42	-620.72	19.55	0.2226	0.1969	0.0883
23	18 - 16	1882.41	963.78	19.55	0.4814	0.0976	0.1776
24	10 - 19	194.49	24.04	3.18	0.3058	0.0130	0.1131

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
25	17 - 20	737.50	-30.68	19.55	0.1886	0.0345	0.0641
26	2 - 21	1895.27	505.98	19.55	0.4847	0.0457	0.1632
27	2 - 22	1272.11	283.09	19.55	0.3253	0.0307	0.1084
28	21 - 10	392.31	-76.16	8.22	0.2386	0.0675	0.0834
29	12 - 19	399.92	-15.47	4.05	0.4937	0.1674	0.1607
30	21 - 12	414.40	-108.07	8.22	0.2521	0.1070	0.0894
31	4 - 23	279.07	1.71	8.22	0.1698	0.0295	0.0575
32	16 - 24	-1441.16	-154.60	19.55	-0.3686	-0.1105	0.1252
33	22 - 6	1012.45	-382.15	19.55	0.2589	0.1376	0.0904
34	9 - 25	151.79	-111.23	8.22	0.0923	0.0272	0.0404
35	14 - 26	316.90	-170.28	19.55	0.0810	0.0139	0.0305
36	18 - 23	384.06	-211.11	9.65	0.1990	0.1364	0.0891
37	20 - 27	660.65	-466.46	19.55	0.1690	0.0763	0.0704
38	25 - 28	50.32	-17.68	3.18	0.0791	0.0179	0.0303
39	21 - 20	2599.75	197.32	19.55	0.6649	0.3887	0.2184
40	16 - 29	1289.48	-348.38	19.55	0.3298	0.1856	0.1154
41	2 - 30	139.61	-37.87	8.22	0.0849	0.0140	0.0300
42	11 - 25	787.60	-67.61	8.22	0.2395	0.0233	0.0815
43	26 - 31	113.48	-46.11	8.22	0.0690	0.0106	0.0259
44	30 - 32	73.40	-36.46	3.18	0.1154	0.0333	0.0479
45	3 - 30	322.09	-147.70	9.65	0.1669	0.0893	0.0709
46	21 - 33	951.71	-118.76	19.55	0.2434	0.0667	0.0803
47	20 - 34	691.91	-493.12	19.55	0.1770	0.0844	0.0740

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
48	33 - 12	389.57	-73.23	8.22	0.2370	0.0664	0.0831
49	20 - 35	1644.49	-1085.63	19.55	0.4206	0.2897	0.1715
50	25 - 36	145.68	-56.50	3.18	0.2291	0.1254	0.0888
51	11 - 36	446.76	-94.50	4.05	0.3677	0.2430	0.1216
52	33 - 37	472.83	-187.84	19.55	0.1209	0.0252	0.0428
53	35 - 38	512.78	227.62	8.22	0.3119	0.0138	0.1157
54	17 - 35	3542.87	-1572.07	19.55	0.6041	0.3313	0.2242
55	35 - 39	1548.44	280.69	19.55	0.3960	0.0633	0.1302
56	37 - 40	289.44	50.66	8.22	0.1761	0.0031	0.0616
57	22 - 30	230.36	-140.12	8.22	0.1401	0.0669	0.0562
58	11 - 41	438.43	-244.69	19.55	0.1121	0.0237	0.0415
59	31 - 42	79.73	-15.62	3.18	0.1254	0.0107	0.0477
60	27 - 34	244.54	-148.84	18.44	0.0663	0.0082	0.0270
61	6 - 43	1126.78	-724.28	19.55	0.2882	0.2000	0.1124
62	36 - 44	466.50	144.05	3.18	0.7335	0.0577	0.2757
63	26 - 41	1471.91	-840.09	19.55	0.3764	0.2521	0.1436
64	36 - 45	48.08	-21.04	3.18	0.0756	0.0109	0.0296
65	6 - 46	2458.66	-632.12	19.55	0.4192	0.2933	0.1420
66	26 - 7	1065.97	-380.28	19.55	0.2726	0.0903	0.0959
67	47 - 48	-1608.73	313.46	19.55	-0.2743	-0.0464	0.0904
68	48 - 49	-5253.52	-472.31	19.55	-0.6718	-0.1535	0.2194
69	49 - 50	8717.95	-1655.49	19.55	0.4459	0.1630	0.1468
70	50 - 51	6000.32	-9.42	19.55	0.3069	0.1403	0.0992

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVar)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
71	51 - 52	598.50	-1144.64	19.55	0.0612	0.0182	0.0436
72	52 - 47	-6678.61	-2390.18	19.55	-0.3796	-0.1214	0.1321
73	49 - 53	2598.28	-575.61	19.55	0.3323	0.2325	0.1101
74	52 - 54	3462.00	962.50	19.55	0.5903	0.1399	0.2008
75	50 - 55	1209.64	-98.96	19.55	0.3094	0.0990	0.1003
76	53 - 56	1983.18	1091.64	19.55	0.5072	0.1376	0.1920
77	52 - 57	2865.68	841.83	19.55	0.7329	0.1528	0.2503
78	51 - 58	1667.37	-448.57	19.55	0.4264	0.3145	0.1457
79	57 - 58	960.31	-591.60	19.55	0.2456	0.1456	0.0969
80	50 - 59	346.18	87.32	8.22	0.2106	0.0062	0.0736
81	49 - 60	209.17	-32.29	8.22	0.1272	0.0240	0.0436
82	51 - 59	1950.80	151.10	8.22	0.3955	0.0933	0.1372
83	55 - 60	772.58	-13.03	8.22	0.3133	0.0416	0.1069
84	58 - 59	1973.53	50.99	8.22	0.4802	0.0580	0.1678
85	52 - 61	810.96	-165.02	19.55	0.2074	0.0581	0.0694
86	52 - 62	109.18	-67.69	8.22	0.0664	0.0117	0.0268
87	47 - 61	1799.90	27.68	19.55	0.4603	0.1801	0.1489
88	49 - 63	1032.58	239.10	19.55	0.2641	0.0166	0.0877
89	58 - 64	547.08	267.77	8.22	0.3328	0.0206	0.1294
90	61 - 54	2223.13	1049.62	19.55	0.5686	0.0828	0.2066
91	47 - 65	1628.33	-128.09	19.55	0.4165	0.2046	0.1351
92	56 - 66	664.41	463.35	19.55	0.1699	0.0291	0.0718
93	63 - 60	337.83	-203.22	8.22	0.2055	0.1449	0.0815

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
94	62 - 67	77.05	-48.26	3.18	0.1211	0.0568	0.0519
95	59 - 68	2072.76	-510.63	8.22	0.6304	0.5941	0.2201
96	54 - 67	394.15	-74.24	4.05	0.3244	0.0833	0.1108
97	57 - 69	1510.84	-1001.38	19.55	0.3864	0.2086	0.1558
98	56 - 70	716.93	-93.17	19.55	0.1834	0.0613	0.0640
99	48 - 65	2184.99	-143.89	19.55	0.5588	0.2490	0.1822
100	59 - 71	1187.41	-332.05	9.65	0.6152	0.5870	0.2468
101	69 - 72	268.04	40.97	8.22	0.1630	0.0072	0.0559
102	71 - 68	1538.41	-76.68	8.22	0.9358	0.0579	0.3176
103	50 - 73	686.31	12.19	19.55	0.1755	0.0226	0.0567
104	68 - 74	2744.64	-705.00	8.22	0.4174	0.2861	0.1461
105	54 - 62	261.00	-156.52	8.22	0.1058	0.0112	0.0434
106	63 - 75	82.52	-59.68	8.22	0.0502	0.0090	0.0210
107	74 - 76	375.94	-158.45	8.22	0.2287	0.0984	0.0851
108	66 - 70	591.37	-390.96	19.55	0.1512	0.0315	0.0637
109	54 - 77	3037.73	-1937.83	19.55	0.3885	0.3001	0.1546
110	69 - 78	465.51	-163.39	19.55	0.1191	0.0221	0.0408
111	74 - 64	1267.91	-221.27	8.22	0.7712	0.6554	0.2683
112	68 - 79	652.76	-19.77	8.22	0.3971	0.1592	0.1347
113	55 - 80	178.52	-29.68	8.22	0.1086	0.0157	0.0376
114	49 - 73	3674.83	-85.80	19.55	0.9399	0.1852	0.3041
115	74 - 81	752.97	244.38	8.22	0.4580	0.0027	0.1650
116	77 - 82	1882.12	-1548.00	19.55	0.3209	0.2497	0.1344

Table A.25: Load-flow solution for 82-bus and 121-line network - line flows (continued).

Line No	Line Term	P_{flow} (MW)	Q_{flow} (MVA _r)	SIL (MW)	$\frac{P_{flow}}{SIL}$	$\frac{P_{flow}}{P_{max,stab}}$	$\frac{I_{flow}}{I_{max}}$
117	73 - 51	1128.31	37.56	19.55	0.2886	0.1179	0.0935
118	5 - 47	745.15	-734.99	18.44	0.2020	0.1077	0.0964
119	3 - 66	20374.44	8127.95	18.44	5.5245	0.5889	1.9806
120	28 - 82	125.34	-289.54	3.18	0.1971	0.0426	0.1821
121	24 - 82	25691.08	-702.55	18.44	6.9661	0.8831	2.4223

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