AN INTELLIGENT ENVIRONMENT FOR THE PRELIMINARY DESIGN OF POWER TRANSMISSION NETWORKS

by

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An Intelligent Environment for the Preliminary Design of Power Transmission Networks

ABSTRACT

The design of AC/DC power transmission networks is a complex, time-consuming problem. Although a variety of power system analysis tools are available for this purpose, planning engineers still rely heavily on their experience to determine which alternative network designs are the most suitable. This is particularly true when multiple measures of evaluation such as cost, reliability and other technical criteria have to be balanced against environmental and socio-economic considerations. The present design practices rely mainly on time-consuming detailed analysis tools thereby restricting the number of designs that can be reasonably processed. Furthermore, much of the available design knowledge is dispersed over numerous sources, particularly the experience of human experts.

In this thesis, a new software tool called TIDE (Transmission Intelligent Design Environment) has been developed which provides the design engineer with a fast, integrated and intelligent environment for the preliminary design of point-to-point transmission systems. The goals of this environment were to identify, model and preserve design expertise in a computerized user-friendly environment, to integrate this expertise with the main network analysis tools (load flow, transient stability, reliability and costing) and to automate the transmission design process. These goals are achieved through an integrated system made up of complementary expert system modules, databases and classical simulation techniques. The expert system modules are particularly appropriate to capture basic design knowledge since design is mainly conceptual, creative and non-algorithmic. A hybrid expert system using object structures and rules was developed for this purpose.

The originality of TIDE lies in the fact that the main power network design tasks and their associated analysis tools are integrated into one design environment. Thus, the conflicting design criteria of overvoltage, steady-state voltage control, stability and reliability are not considered independently but in a holistic approach which examines a number of possible design tradeoffs. These include AC versus DC transmission, system voltage versus number of lines or compensation levels, series versus shunt compensation and reliability versus cost. The intelligent system considers and analyzes a wide spectrum of potential designs. Out of these, a reduced set of feasible designs along with their costs and performance characteristics are presented automatically to the planner who can subsequently perform sensitivity analyses on system flexibility, stability criteria, reliability levels, component cost and number of spares. TIDE was validated by comparing its results with a number of actual systems.

Un Environnement Intelligent pour la Conception Préliminaire de Réseaux Électriques de Transport.

RÉSUMÉ

La conception des réseaux de transport CA/CC est un problème complexe nécessitant un temps de calcul très long. Bien qu'une variété d'outils d'analyse de réseaux soient disponibles à cette fin, les ingénieurs de planification comptent encore fortement sur leur expérience pour déterminer quelles conceptions alternatives de réseau sont les plus appropriées. Ceci est particulièrement vrai quand des critères multiples comme le coût, la fiabilité et d'autres critères techniques doivent faire face à des considérations environnementales ou socio-économiques. Les techniques actuelles de conception reposent principalement sur des outils d'analyse détaillée qui consomment beaucoup de temps et de ce fait, elles sont restrictives sur le nombre de conceptions qui peuvent être raisonnablement analysées. De plus, la plus grande partie de l'expertise disponible en conception se retrouve disséminée dans nombreuses sources, particulièrement dans l'expérience de nombreux experts de ce domaine.

Dans cette thèse, un nouvel logiciel appelé TIDE (Environnement intelligent de conception pour réseau de transport : " Transmission Intelligent Design Environnement ") a été développé et fournit à l'ingénieur de conception un environnement intelligent intégré et rapide pour la conception préliminaire de réseaux de transport point à point. Les objectifs de cet environnement étaient d'identifier, de modéliser et de préserver l'expertise de conception dans un environnement informatisé convivial, d'intégrer cette expertise avec les principaux outils d'analyse de réseaux (écoulement de puissance, stabilité transitoire, fiabilité et établissement des coûts) et d'automatiser le processus de conception du réseau de transport. Les objectifs sont atteints à travers d'un système intégré complété par des modules de système expert complémentaires, des bases de données et des techniques de simulation classiques. Les modules de système expert sont particulièrement appropriés

pour acquérir l'expertise élémentaire en conception puisque celle-ci est principalement conceptuelle, créative et non algorithmique. Un système expert hybride utilisant des structures objet et des règles a été développé à cette fin.

L'originalité de TIDE repose sur le fait que les tâches de conception du réseau principal et les outils d'analyse associés sont intégrés dans un environnement de conception unique. Ainsi, les critères de conception incompatibles de surtension, du réglage de tension en régime permanent, de stabilité et de fiabilité ne sont plus considérés indépendamment mais dans une approche holistique qui examine un nombre possible d'échanges dans la conception. Ceci inclut le transport CA comparé au transport CC, la tension du réseau comparée au nombre de lignes ou aux niveaux de compensation, la compensation série comparée à la compensation shunt et la fiabilité comparée au coût. Le système intelligent considère et analyse un large spectre de conceptions possibles. Parmi celles-ci, un ensemble réduit de conceptions réalisables données avec leurs coûts respectifs et leurs caractéristiques de performance sont présentées de façon automatique au planificateur qui subséquemment effectue des analyses de sensibilité sur la flexibilité, les critères de stabilité, les niveaux de fiabilité, le coût des composants et le nombre de pièces de rechange. TIDE a été validé en comparant ses résultats avec plusieurs réseaux réels.

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My heart is truly overflowing with gratitude firstly to God and then to the numerous people who believed in me and encouraged me along in this thesis.

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AC	Alternating current.
AI	Artificial Intelligence.
CEA	Canadian Electrical Association.
CIGRÉ	Conférence Internationale des Grands Réseaux Électriques.
DC	Direct current.
EPNS	Expected power not supplied.
EPRI	Electric Power Research Institute.
ERIS	Canadian Electrical Association's Equipment Reliability Information System.
ES	Expert systems
FVP	Flat voltage profile.
HQ	Hydro-Québec.
ILDC	Inverted load-duration curve.
LF	Load flow.
LOLP	Loss-of-load probability.
LP	Linear programming.
NERC	North American Electric Reliability Council.
p.u.	Per unit.
SC	Series capacitance.
SIL	Surge impedance loading.
SL	Shunt inductance.
SPS	Special protection scheme.
SS	Substation.
SVC	Static VAr compensation.
TIDE	Transmission Intelligent Design Environment.
TOV	Temporary overvoltage.
VAr	Volt-Amperes reactive.

LIST OF SYMBOLS

α	Attenuation constant of transmission line.
$\angle\alpha$	Angle of ABCD parameter A.
β	Phase constant of transmission line.
$\angle\beta$	Angle of ABCD parameter B.
γ	Propagation constant of transmission line.
ΔP_i	Power state reduction of state i.
ΔV	Transmission line voltage regulation.
δ	Voltage angle.
δ_c	Clearing angle.
δ_{max}	Maximum swing angle.
δ_o	Steady-state system angle at full power.
λ	Failure rate.
μ	Repair rate.
l	Transmission line length.
l_{eq}	Equivalent line length (shortened by series compensation).
A	Element (1,1) of the ABCD matrix.
A_{acc}	Accelerating energy (area).
A_{dec}	Decelerating energy (area).
af	After fault.
aux	Auxiliary components.
AV_i	Availability of component i.
b	Line shunt susceptance.
B	Element (1,2) of the ABCD matrix.
C	Element (2,1) of the ABCD matrix.

cbdl	Conductors per bundle.
C_i	Cost of component i (generation, transmission lines, etc...).
cir	Circuit.
cond	Conductor.
D	Element (2,2) of the ABCD matrix.
E	Internal generator voltage.
EPNS	Expected power not supplied.
f	System frequency.
gen	Generation.
H	Inertia of generator or load.
HL	Heavy loading conditions.
I	Current.
ILDC	Inverted load-duration curve.
k	Constant.
k_{Tloss}	Terminal losses expressed as a percentage of the station power.
line	Transmission line.
LL	Light loading conditions.
Lloss	Line loss.
LOLP	Loss-of-load probability.
loss	Losses (line or terminal).
n	Number of circuits, substations, etc...
${}^nC_r$	Combinations of r items from n different items or $n!/(r!\ (n-r)!)$.
n_{rel_out}	DC reliability criterion of the number of bipolar circuits lost.
P	Power or Probability (depending on context).
P_e	Generator electrical power.
P_m	Generator mechanical power.
P_{max}	Maximum transmitted power.
P_{min}	Minimum transmitted power.
P_{rel_loss}	DC reliability power loss criterion.
Q_i	Reactive power of component i.

r	Line resistance.
S	Power (real and reactive power).
sc	Series capacitance expressed as a fraction of the line reactance x.
SC	Total series capacitance of the complete transmission line (S).
sl	Shunt inductance expressed as a fraction of the line shunt susceptance b.
SL	Shunt inductance of the complete transmission line Ω.
SS	Substation.
SVC	Static VAr compensator.
t_c	Clearing time.
TC_i	Total cost of component i.
term	Terminal.
Tloss	Terminal loss.
TOV	Temporary overvoltage.
TOV_{MAX}	Maximum temporary overvoltage.
tsf	Transformer.
U_i	Unavailability of state i.
unrel	Unreliability.
V	Voltage.
V_r	Voltage a receiving end bus (load).
V_s	Voltage at generator bus (source).
x	Reactance.
x_d	Generator synchronous reactance.
x_d'	Generator transient reactance.
Y	Shunt impedance.
Z	Series impedance.
Z_c	Characteristic line impedance.

CHAPTER 1

INTRODUCTION

1.1 Power System Planning

The main stages in power system planning are forecasting and collecting the basic data, defining performance criteria, selecting appropriate alternatives, analyzing the technical, environmental and economic properties of each of these alternatives, performing a sensitivity analysis of various parameters, and finally choosing the optimal solution [45]. This planning process normally involves at least two steps, *preliminary design* to reduce the number of alternatives based on simple analysis tools and *detailed design* of this reduced set of alternatives. The more sophisticated and thorough the preliminary design, the smoother is the transition between preliminary and detailed stages and the result is generally shorter detailed analysis and superior designs.

There is no standard procedure in planning power systems and this exercise relies heavily on the experience and intuition of system planning engineers. The present role of the system planner is to conceive possible network solutions and then use existing computer programs to evaluate such solutions [31].

As power system planning progresses, the planner's focus shifts from general preliminary system concepts to specific detailed component additions and changes. This transition necessitates an increase in modelling accuracy and the consideration of more details. Precise system models, however, can be unwieldy to use and are very time consuming for iterative searches and sensitivity analyses. Therefore, to avoid long and expensive analysis, it is of paramount importance that the planner be able to quickly narrow down the possible scenarios. This is only possible if the planner is presented with concise preliminary results in the first stages of the design process.

Power system planning and analysis tools usually focus on a specific task and detailed, integrated models covering all aspects of planning do not exist [31]. Specific tools have inherent assumptions of independence necessitating simplifications in data and modelling. If the assumptions of independence are too severe, then the planning process becomes iterative to ensure coherence between the tasks. Thus, planning is dissected into small, manageable tasks and the results reintegrated to provide a global solution.

There are many different aspects of power system design requiring creativity, intelligent decision capability, and the experience of a system planner. The design process followed by expert planners combines numerical power system analysis tools with an ability based on experience and judgement to limit the number of possible alternative designs and to evaluate and compare their performance so as to arrive eventually at an acceptable compromise. With the recent development and proliferation of expert system technology [36], computers now have the capability to encapsulate this diverse range of tasks in an integrated design environment and thus aid the planning engineer enormously.

The focus of this research is to demonstrate the feasibility of such a design environment based on expert systems, to detail its structure and to provide an example in the form of an intelligent preliminary point-to-point power system transmission design.

1.2 Preliminary Point-to-Point Transmission System Planning

Transmission planning involves studying methods of transmitting large amounts of electrical power primarily from generation to load centres but also among various network points. Transmission enables the development of more remote generation and could account for 25 to 35% of the power system's investment costs [31]. Point-to-point transmission refers to a transmission system between two separate points, normally a generation source and a load centre.

The differences between preliminary and detailed transmission planning are characterized by the type of analysis tools, the time to perform the analysis and the accuracy. Preliminary design is a conception phase using simple analysis tools or standard lookup tables or graphs [59] to approximate the main system characteristics. It is performed in a relatively short time, depending on the expertise of the planner, and screens prospective alternative designs. By way of contrast, detailed design, requiring days to simulate, uses sophisticated analysis tools, and results in system plans ready for construction. The main analysis tools for detailed transmission design are load flow, transient stability, reliability and costing tools requiring an experienced designer to manage and interpret data so as to evaluate and optimize prospective designs.

1.3 Motivation

This thesis develops a planning tool using expert systems [48],[95],[103] to automate the preliminary design process of an AC/DC transmission system incorporating the basic knowledge and analysis tools of transmission design. The goals of this project are to identify, model and preserve an expert's planning and analysis methodology in an user-friendly environment, to integrate planning tools and to automate the design process while explaining its methodology. The culmination of this project is a hybrid package, called TIDE [40],[37], combining expert system modules and classical power system simulation tools.

The motivation behind this research is to mitigate the loss of planning expertise, improve the ability to capture design expertise, raise the reasoning level of the system planner, bridge the gap between preliminary design and system design methodology, extract and define planning methodology and design criteria, and integrate the relevant power system analysis tools. The motivation for this work is further discussed in the paragraphs that follow.

1.3.1 Loss of Expertise

A wealth of power system planning expertise has been amassed over the years of tremendous growth and expansion of the transmission networks during the period from 1960-1980 [59]. As many North American power systems reached maturity, load growth has been steadily declining causing utilities to downsize their planning staff. Other pressures, including environmental constraints and demand-side management, are decreasing the number and size of system expansion projects and lengthening the time between such transmission projects. With an ageing population of experienced planners, there is a real risk that this expertise will be permanently lost. In the long run, power transmission expansion will always be a necessity but the expertise of experienced system planners may not be there unless steps are taken to preserve it.

1.3.2 Ability to Capture Design Expertise

Fortuitously, as the population of experienced planners diminishes, the ability of new computer programs to capture this type of knowledge is becoming increasingly more powerful. This potential for the preservation of expertise in a readily usable form is a recent phenomenon [99]. Expert systems have reached a point of maturity where they can readily encapsulate design expertise. There is now the unique opportunity to preserve design expertise in a manner that can approximate an expert's knowledge and design methodology all the while explaining the decisions being made.

1.3.3 Raising Reasoning Level of the System Planner

The system planner is presented with many isolated analysis tools. Attempts of the more entrepreneurial power system planner to integrate software packages results in the use of generic programs such as spreadsheet analysis or simple hand calculations. Both of these methods require data transformations and manipulation, thereby shifting the planner's focus from designing alternatives to obtaining suitable computer systems. To be effective, a planner should be able to reason at a higher level and to study the ramifications of various design criteria and constraints. Without an integrated design environment this would otherwise be prohibitive due to computational or time constraints. In an integrated environment, tradeoffs are demonstrated at an early stage in the design process, thereby readily identifying feasible systems for further in-depth studies. Thus, a thorough preliminary design process is assured.

1.3.4 Bridging the Gap Between Preliminary Design and Detailed Design

Presently, when designing a power system, there is a hiatus between the preliminary stages of design and the comprehensive analysis required to arrive at the final design. Preliminary design methods are ad-hoc and very often rough hand-calculated approximations relying heavily on the designer's expertise [84]. Detailed system design, however, necessitates in-depth, sophisticated analysis requiring an experienced design engineer. The majority of power system analysis tools are very sophisticated which, when isolated, are unsuitable for preliminary design. There is a need to bridge this gap by automating aspects of the design process so as to render these tools manageable for system design.

1.3.5 Defining Methodology and Design Criteria

When developing such an integrated design environment, power system knowledge must be acquired from planning experts. This necessitates the identification of transmission design methodology and criteria on which to base the merits of differing designs. Thus, as this preliminary transmission planning tool was developed, not only was the experience and knowledge being identified and classified, but it was put into a readily usable form.

1.3.6 Integrating Various Power System Tools

Many power system analysis tools already exist that are used in planning. Most of these tools were designed for detailed analysis and in their present form are not available in an integrated design environment for the type of iterative analysis required in system planning. Efficient and thorough system planning requires planning tools readily accessible through a single common interface combined with an automated iterative search process.

1.4 Thesis Objectives

The objectives of this research are to identify, model and preserve expert preliminary transmission planning and analysis methodology in a user-friendly environment, to integrate planning tools and to automate the design process while explaining its methodology and guiding the user. A hybrid tool of databases, expert systems and simulation packages will be developed to achieve these objectives. The scope of this research is limited to the preliminary design of point-to-point transmission systems. This type of design can be used to integrate new generation into an existing system or to increase the capacity of an existing transmission system.

Inherent in the expert's design methodology are the objectives of designing a robust, simple, flexible and reliable transmission system at minimal cost. The desired output of this design package is a list of feasible preliminary transmission designs which meet a set of design criteria. The design's costs and electrical performance are also evaluated. The design criteria include temporary overvoltages, load flow feasibility, stability, voltage profile, reliability, as well as equipment ratings.

The design variables included are: type of transmission (AC or DC), voltage class, number of substations, compensation levels and location as well as transformer and switching requirements. The power system analysis tools used are load flow, transient stability, reliability as well as system costing. The simulation tools, databases as well as the expert systems must be integrated efficiently.

The resulting preliminary design environment should enable parametric sensitivity studies to be performed on most system data and design criteria such as types of equipment and their costs, design criteria including stability and the effect of system reliability. From this analysis, generalized transmission results can be obtained.

1.5 Thesis Outline

Chapter 2 outlines previous research dealing with methods and integrated design tools for transmission planning.

Chapter 3 describes the preliminary point-to-point transmission planning problem and contrasts it with detailed transmission planning. Inherent simplifications of preliminary planning are identified and their resulting implications on the design process are discussed. Design criteria, which assure the prescribed power system performance, are enumerated and the components which affect the criterion are identified. The design process presently used by planning engineers also is discussed.

Chapter 4 proposes an automated integrated intelligent preliminary transmission design environment. Initially, a variety of artificial intelligent tools are introduced and compared. Subsequently, a history of TIDE is recounted indicating the developmental process of such a design tool.

TIDE is introduced by outlining the structure, interaction and integration of the various design tools. Further background is provided by indicating how the diverse design tasks are solved using appropriate analysis tools. The three main categories of tools are databases, expert systems and simulators. In each of these categories, the ability to efficiently solve specific tasks is described. Finally, an overview of the actual preliminary transmission planning environment is provided.

Chapter 5 demonstrates the usefulness and the features of the previously described intelligent design environment by comparing the designs proposed by TIDE with a number of existing transmission networks. Specific design examples are discussed and the influence of various design criteria are explored. More global planning trends, spanning a wide range of designs, are subsequently investigated and general transmission trends are described.

Chapter 6 summarizes the abilities of the preliminary transmission design environment, points out the original aspects of this research, and proposes further enhancements to the environment.

Appendix A shows typical screens of a design session using TIDE including databases, design criteria, design options and transmission design results.

Appendix B summarizes the equipment database and design criteria used in the design examples in this thesis.

Appendix C details the reliability states of the Manicouagan system design example.

Appendix D outlines the design knowledge of the AC and DC design expert systems.

Appendix E contains the electrical component models and network formulae used in TIDE's simulators.

Appendix F describes the costing formulae used in TIDE.

CHAPTER 2

SURVEY OF TRANSMISSION PLANNING LITERATURE

2.1 Introduction

As long as it remains economical to build large centralized generation sites, it will be necessary to transmit large blocks of power over long distances [31]. The potential for low-cost power near load centres has been nearly exploited, however, bulk hydro power and coal fields still exist, although often at long distances from the load centres [92]. Further pressure from environmental constraints also tend to locate generation centres away from inhabited areas [59]. Examples of such regions are found in China and Brazil where very long AC and DC EHV transmission lines are planned for the next 15 years [12]. Thus, with the ever increasing level of world electrification and interconnection, there will continue to exist a need to connect generation to loads until the design of new technology is developed which can efficiently generate electric power locally while respecting environmental laws. Therefore, the challenge remains to develop tools to explore the various options of exploiting distant power sources and transmitting the generated power efficiently and reliably to the desired load centres [92].

This chapter surveys and compares the main published techniques and tools available to transmission planning engineers. Chapter 3 describes in detail the methodology of transmission planning with particular emphasis on point-to-point transmission.

2.2 Survey of Transmission Planning and Design Methods

2.2.1 Introduction

The various methods developed for the expansion of transmission networks can be divided into two main categories, design and planning. Design considers the requirements of the power system at one moment in time whereas planning focuses on the future needs over a horizon of anywhere from 1 to 50 years [31]. Most methods described in the literature are planning methods which determine the location, type and timing of transmission facility additions. It is interesting to note that although there exists a wide variety of analytic tools and methods for long-range transmission planning there has been very little usage of these analytic approaches in industry [64]. This may be due, in part, to the oversimplification of the models used, the great degree of uncertainty in forecasting the future, as well as in the risks involved in making substantial monetary investments.

A survey conducted by EPRI [64] indicates that the most important factors in system modelling for transmission planning are capital equipment costs, reliability (including cost versus reliability tradeoffs), environmental impact, component limitations, losses, ease of data entry, speed of analysis and effective tools for representing the results. Some of the major weaknesses identified in the models pertaining to system design were the need for flexibility of the design [57] and for environmental considerations [50].

The goal of this thesis is the preliminary design of a long-line addition in a specific location of an existing network. This literature survey will focus, therefore, on modelling and design techniques rather than on planning new additions over time and deciding where these should be placed within the network.

In this survey, a distinction is made between methods and integrated tools for transmission planning and design. Methods are basically mathematical optimization programs where the variables being optimized are the transmission system parameters (e.g.

lines, VAr sources) and where the goal is usually to minimize the capital investment cost. In contrast, planning and design tools are more complex packages that integrate, usually in a computer environment, a number of design methods and simulation tools as well as data bases, manuals and graphical interface tools.

2.2.2 Transmission Planning and Design Methods

The basic simulation analysis and design programs for transmission systems are:

- load flow
- security
- optimal power flow
- short-circuit
- transient stability
- reliability
- cost estimation.

Two main types of design methods can be identified, those where the design is left entirely up to the planner [76] who then manipulates the above mentioned programs to arrive at a final design, and methods based on optimization techniques which automatically manipulate the above basic programs as part of the optimization process.

The methodology followed in design methods, relying mainly on the system planner, is usually indirectly included as part of published specific case studies. Examples of such case studies are found in [51] and [52]. The former, for example, describes a planning method for a longitudinal system where oscillatory stability is explicitly accounted for by using eigenvalue analysis. This design criterion is then compared against other technical factors such as maximum power transfer, fault current, transient stability and system losses. In section 2.3 which follows, several integrated tools are described which expand on this type of methodology.

The literature also describes several methodologies used in transmission expansion based on the optimization approach, namely, linear programming [64], integer [29],[89] and mixed-integer programming [33],[93], dynamic-programming [64], branch-and-bound [94], the maximum principle of Pontryagin [58], the Hopfield model combined with simulated annealing [63] and simulated probabilistic techniques [61].

The long-term transmission network expansion planning problem is a multi-staged, nonlinear, combined discrete and continuous variable optimal control problem. Because of this complexity, relatively simple power network models must be used. In particular, the load flow is often modeled by the DC model (DCLF) and even by the transportation model. Both of these models have severe limitations especially when it is important to characterize transmission losses as well as voltage and VAr phenomena as found in long transmission lines [76]. In addition, optimization-based expansion planning often fails to model critical considerations such as transient stability, short-circuit, contingency analysis and even reliability as these would make the problem even more intractable.

A comprehensive review of mathematical expansion planning methods up to 1980 can be found in [64]. Several of the principal transmission design methods based on mathematical optimization found in the literature up to 1994 are now summarized below.

CHOPIN [58] is a static optimization tool which decomposes the investment and operation problems into subproblems. Heuristics are used to solve the investment model based on the idea that a reasonable initial plan can be systematically improved by modifying one parameter at a time. The load flow is modelled by the DCLF or by a Transportation Model or combinations of these. In addition, CHOPIN analyzes a user-specified list of contingencies.

Classical linear programming (LP) models use a linear cost model and a transportation-type model system representation. The linear model has the advantages of being very rapid, having a provable global optimum which can be found in a limited number of steps and can provide sensitivity information about how the object function would change if a given limit was relaxed [64]. LP is also used in decomposition techniques such as that described by Levi and Calovic [62] where the investments and the system operation are separated into two independent problems and solved iteratively.

A mixed-integer programming approach is used to produce physically realizable plans of discrete line additions. One such example is a static synthesis network formulation proposed by Santos et al. [93] which considers fixed and variable costs of new equipment and uses an implicit DC load flow to model the transmission network.

Kim et al. [58] propose a solution to the long-term investment planning problem based on the Maximum Principle of Pontryagin. The yearly optimal operation problem, including the probability of line failures is solved through a LP assuming a DCLF.

When the long-term expansion problem is decomposed into yearly and overall optimization problems, heuristics are often used to improve the performance of the yearly expansion scenario optimization by limiting the number of unreasonable or inadequate states considered. This usually involves guiding branch-and-bound techniques, evaluating the various power system expansion options and making decisions for future line construction additions. Heuristics are either imbedded directly in the code [58] or form part of supporting expert systems [94].

Heuristics are also used in a hierarchical Benders decomposition integer programming approach described by Romero and Monticelli [89],[90]. Their heuristics were found to be an effective way to cope with the non-convexity of the global optimization. This method decomposes the problem into investment and operation subproblems. These are solved in three stages each of which uses a progressively more accurate power system model, beginning with a Transportation Model and ending with a DCLF.

Other methods proposed by the literature include a Hopfield representation discussed by Liangbao and Yuanda [63] which uses simulated annealing to avoid local minima. Investment and operating costs are considered for the static optimization of line additions. Another method suggested by Youssef and Hackman [110] is a dynamic optimisation model which includes the AC load flow (ACLF) as constraints. The ACLF enables operational and security constraints such as voltage magnitudes and steady-state system angles and is very important for long line preliminary transmission planning [16]. A continuous nonlinear approximation of the number of line additions is used to avoid the problems associated with integer programming. The global system problem is solved using MINOS/Augmented routines which implement the projected Lagrangian algorithm.

The limitations of transmission expansion planning and design based on mathematical programming are numerous. Among these, one can include: very simplified models, long computational times, exclusion of some practical limitations, and oversimplification of some design criteria. The results of these programs can therefore be treated as only part of the overall planning process. The next section describes a set of tools available in the literature which attempt to model a broader part of the planning process by integrating a number of design methods.

2.3 Survey of Transmission Planning and Design Integrated Tools

2.3.1 Introduction

A problem which power system planners face is the lack of integration of the various power system analysis and design methods. Although some attempts are being made to develop design environments which facilitate the interaction among such programs, this is not an easy task [22]. In part, this difficulty is due to the dimensionality of the problem and to our inability to develop a software to optimize every aspect of transmission expansion planning. As a result, commercial packages, although partly based on optimization principles, also resort to heuristics and human intervention to account for many of the problem complexities [64]. The integrated design tools discussed below range from simple manuals with lookup tables to guide the user, to computer-based integrated design and planning environments.

2.3.2 U.S. Department of Energy (DOE) Design Tool

An example of a tool developed for generic overhead transmission system design is described in [25]. This tool is presented in the form of a manual. Calculations are performed using simple heuristic formulae supplemented by constants provided by tables and graphs determined by various detailed simulations and generalized for usage in the design of typical transmission systems. The aim of this tool is to provide a reasonably accurate definition and comparison of transmission systems with relatively small time and effort. The systems modeled range from 362 to 1200 kV AC and from ±400 kV to ±800 kV DC. The power transmitted can range from 3 to 16 GW over distances of 100 to 1200 miles. The lines could be series-compensated up to 60% while the fault clearing times were assumed to range from 1 and 3 cycles.

This design manual facilitates the development of workable transmission alternatives, transmission voltage, number of circuits, series compensation, shunt capacitance, as well as providing estimates of benefits and total cost. Other factors such as estimates of corona loss, environmental effects, right-of-way requirements, visual impact and material usage are also considered. The method is based on heuristics which ensure relatively sound designs.

The stability modules are based on the equal-area criterion or on the maximum steady-state transmission limit angle [71]. Reliability is, however, not explicitly considered.

The strength of this model is that it provides a simple method of designing preliminary transmission systems based on average system parameters. The tables used to perform the analysis rely on the generalization of the results of many simulations. The manual also warns the user about the strengths, weaknesses as well as the accuracy of the methodology so that the planner can judge the level of confidence in the results.

The main weakness of this method is that it is based on tables and curves which are in turn obtained from average parameter values. The method also requires simple hand calculations and each network design alternative considered must be recalculated. As new conductors arrive and prices vary, new tables would have to be regenerated and the manual updated.

2.3.3 Decision Support System (DSS)

DSS is an interactive software package for power system planning which includes load forecasting, generation and transmission expansion as well as a financial assessment module [22]. The transmission expansion planning subprogram contains three models, an electric power and energy balance used to determine required interregional transmission requirements, a financial assessment of transmission expansion model to compare various alternatives and a DC load flow model to determine if the proposed alternatives are acceptable. Access to these modules and database is provided by a friendly and interactive user interface.

2.3.4 Electricité de France Design Tool

A design environment developed by EDF is called PLANTINE [10] which integrates load flow, stability, short-circuit and reliability tools through graphical interfaces and common databases. Data may be extracted and reduced for specific regions of the network to facilitate analysis and planning. Although this environment does not contain a tool to perform the actual design, it does, however, facilitate the designer's planning work by providing an integrated environment.

2.3.5 Brazilian Long Distance Planning Tool

Another planning environment is being developed by Centro de Pesquisas de Energia Elétrica (CEPEL) [34] in Brazil which is comprised of a set of power system planning and analysis tools. A graphical user interface provides access to a long-term transmission expansion module which is supplemented by design modules such as an optimal power flow, a VAr allocation utility and a composite generation-transmission reliability program. The long-term transmission planning module uses a dynamic expansion planning process to select circuit additions based on cost sensitivity indices [92].

2.3.6 Power Technologies Inc.

PTI has an interactive software package called TPLAN [85] which uses the DCLF to provide the user with a list of overloaded lines ranked by sensitivities to line impedances. The user can select line additions and interactively view the effect on the overall system line flows and cost. Once system additions have been determined, reliability criteria can be calculated based on AC load flow contingency analysis.

2.4 Summary

Many different methods and integrated tools have been proposed for transmission network design and planning. Some methods make use of readily available optimisation packages and are very efficient at obtaining non-discrete optimal results but deteriorate in efficiency when optimizing discrete quantities. Most methods use simple linear models ignoring nonlinear constraints on real and reactive power. Modelling accuracy may be improved through the use of integer decision variables but this restricts the optimisation to relatively small systems due to large storage and computational requirements. Larger systems can be analyzed by reducing the search space through branch-and-bound techniques, however, these methods, although much more rapid, cannot guarantee optimality and the results are highly dependent on the criteria used to bound the search space.

The available integrated tools, although more effective than pure optimization-based approaches, still require considerable intervention by the designer and are far from being automatic or intelligent.

CHAPTER 3

PRELIMINARY POINT-TO-POINT TRANSMISSION DESIGN

3.1 Introduction

A transmission network design problem is a complicated, iterative process in which a wide range of possible transmission systems are formulated, analyzed and modified to meet the system requirements. The system planner begins by identifying and defining the desired system characteristics and how they can be realized in general terms. As superior transmission designs are generated, the system planner's focus shifts from a simple, screening type of comparison to an in-depth analysis of a few alternatives. From the conception phase to the final design there is an increase in the problem complexity, depth of analysis and modelling accuracy of the designs. Throughout the design process, transmission system planners rely on their experience to ensure a thorough process culminating in a best detailed design.

The ensuing discussion presupposes that prospective bulk power transmission corridors have been identified through regional planning studies comprising load forecasting and generation planning [31], [98]. Foreseen regional energy interchange and expansion plans are synchronized by matching major load centres with potential generation sites. Viable transmission corridors are then identified taking into account environmental and socio-political constraints. The most suitable transmission system to supply this power to fixed geographic locations can now be designed [92]. The design of a transmission system between two fixed areas is called point-to-point transmission design and constitutes the focus of this thesis.

This chapter outlines the power system transmission design process which provides the framework for a proposed intelligent design environment for point-to-point transmission design. The design process is introduced by showing the difference between the two major design stages, preliminary and detailed design. This is followed by a description of relevant design criteria and other design considerations. Finally, a preliminary design methodology for both AC and DC transmission systems is discussed.

3.2 Preliminary versus Detailed Transmission Design

The initial phase of transmission design is called *preliminary* transmission design. At this stage, possible transmission designs are screened to select superior preliminary designs for further study. The *detailed* transmission design phase uses the superior designs identified in the preliminary screening as a starting point for in-depth analysis so as to arrive at a best design. The boundary separating the preliminary and detailed design stages is not well defined and is continually narrowing due to improvements in the preliminary design process brought about by the integration of power system design tools.

The proposed integrated design environment of this thesis (see Chapter 4) redefines the preliminary stage by moving it closer to the final design stages. This is accomplished by taking the relevant expertise from the preliminary design process and refining it in such a way so as to lead to a finite number of realistic final design alternatives. As a first step, it is necessary to state the assumptions behind the modelling techniques used in each of the design stages.

The present scope of preliminary and detailed design along with the proposed preliminary design environment of this thesis are illustrated in Table 3.1 (Overview), Table 3.2 (Analysis) and Table 3.3 (Component models). These tables indicate the degree of complexity involved in each design stage. The overall differences, summarized in Table 3.1, can be quantified by the time required to perform the analysis, the amount and type of data required, the sophistication and complexity of the tools used to predict system behaviour and the level of detail of the results. Traditionally, preliminary design is performed very quickly using simple tools, if any, but a single solution may still take minutes to obtain. The proposed method takes seconds and yields a set of feasible solutions rather than a single one. The input data ranges from the basic problem definition of power and distance to the detailed representation for each component. Preliminary transmission design tools are generally quite restrictive in scope and accuracy whereas detailed design involves high-level analysis to precisely determine system operation. In the proposed preliminary design tool, more detailed models are used for phenomena such as transient stability, load flow and overvoltages.

Table 3.1: Preliminary vs Detailed Transmission Design Overview.

	Preliminary		**Detailed**
	Existing	**Proposed**	
Analysis Time	Minutes-hours	Seconds-hours	Days-months
Inputs	Power, distance	+ Fundamental system component characteristics and costs	+ More detailed representation including time dependency
Tools	Curves, tables, experience, approximations.	+ Better models and integrated system	Separate complex simulation tools
Results	Approximate design	More elaborate approximate designs, automatic solutions	Final system design

A detailed listing of the main electrical analysis tools and their abilities are shown in Table 3.2. A comparison of the equipment component models is shown in Table 3.3. A detailed table of the component models for the proposed environment is given in Appendix E.

Table 3.2: Preliminary vs Detailed Transmission Design Analysis.

	Preliminary		Detailed
	Existing	Proposed	
Overvoltage	Not considered or lookup tables	Load rejection in steady-state	Temporary overvoltages using EMTP or TNA
Voltage Profile	Not explicitly considered	Flat profile for heavy and light load using VAr compensation	Bus voltage magnitudes within limits for all operating conditions
Load Flow	Non-existent or highly simplified	AC load flow for the new addition to the network	Complete network AC analysis
Stability	Heuristic based on system angle	Equal-area criterion	Complete transient stability incorporating all control features considering multiple credible contingencies
Reliability	Respecting deterministic design practices	+ Probabilistic state analysis for new addition	+ Complete network analysis, increased system modelling accuracy
Costing	Quick estimates	Investment, losses, reliability penalties	Complete detailed economic analysis over planning horizon.

Table 3.3: Preliminary vs Detailed Transmission Design, Equipment Models

	Preliminary		Detailed
	Existing	Proposed	
General Specifications	IEC standards	+ Nominal Voltage, AC or DC, equipment requirements and ratings	Individual component specifications
Generation	Power	+ Lumped inertia, synchronous and transient reactances	Machine and load dynamics, protection
Transformers	Ratings	+ Series reactance	+ Saturation characteristics and taps
DC Terminals	Ratings	+ Number of poles	+ Terminal design, control circuits, filter and compensation design
Transmission Lines	Voltage, number of circuits, series impedance	+ Series and shunt impedances, distributed model, insulation levels, conductor size	+ Tower design, routing, visual and environmental impact
Series Capacitors	Ratings	+ Series impedance	+ Protection and control circuitry
Shunt Reactors	Ratings	+ Shunt impedance	+ System performance requirements
Static VAr Compensators	Ratings	+ Constant impedance or constant voltage	Controlled impedance including dynamic control system
Substations	Ratings, Number	-	Component design and reliability analysis, one-line diagram
Load	Infinite bus	-	Actual types with appropriate modelling

In addition to the differences shown in the above Tables, detailed design has to consider a number of specific points such as river crossings and other geographic obstacles, right-of-ways, climatic conditions and the impact on the environment [43].

3.3 Design Criteria

A planning engineer is required to make decisions regarding the acceptability of the system design based on recognized standards and utility norms called criteria. The criteria ensure that the transmission network designs are realizable and will withstand the rigours of system operation. They also provide a rational basis for the choice of one design alternative over another by the degree with which they conform to these accepted standards. The actual values that define the criteria reflect the levels acceptable for the country or region concerned. These values have typically evolved from a consideration of the requisites and constraints particular to the operating environment involved [45]. The design criteria values used in this thesis are outlined in section B.2.

Defining design criteria is very important as they direct all the principal design activities. Most North American utilities presently use deterministic criteria for transmission planning based on standards such as those of the Northeast Power Coordinating Council [81],[79],[80] and Hydro-Québec [52],[84].

The criteria used in preliminary transmission design include system *operability*, *simplicity*, *reliability* and *flexibility*. Among these, operability and reliability are quantitative design standards, whereas system flexibility and simplicity are harder to quantify. Many criteria are also of the so-called *umbrella type* which cover a wide range of conditions. An example is the three-phase system stability criterion which also ensures stability with respect to several other types of less severe faults.

System Operability criteria include voltage control, load flow feasibility, system stability and DC integration into the existing AC system. These are summarized in Table 3.4 and discussed below.

Table 3.4: Transmission Design Criteria

Criteria	**AC Design**
Voltage	TOV limited for load rejection Flat profile for heavy and light load
Load Flow	Feasible at full load with n line sections out
Stability	Fault (3 or 1 phase) under full load followed by loss of m line sections
Reliability	Acceptable LOLP and EPNS Adequacy and security
Component	Operation within component ratings
	DC Design
Voltage	Maximum voltage drop
AC System Integration	AC stability not affected by loss of n poles of bipolar DC line
Reliability	Acceptable LOLP and EPNS Adequacy
Component	Operation within component ratings

Voltage control covers two topics: limiting AC temporary overvoltages (TOV) and transmission line voltage regulation for various system loading conditions. System temporary overvoltages are caused by lightning, switching and load rejection. The first two phenomena are not considered in preliminary planning and form part of the protection scheme and the insulation coordination design. Overvoltages caused by load rejection are due to the Ferranti effect, which is a voltage rise due to the capacitive current flowing through the line inductance of unloaded AC lines [105]. Steady-state voltage profile is maintained through the use of tap-changers and by reactive control provided by generators, shunt capacitors/inductors and static VAr compensators. Usually, heavy and light system loading are the two extreme conditions considered when determining the system steady-state VAr requirements. In the preliminary design of DC systems, there is no explicit voltage control. In such cases, voltage regulation depends on the voltage level, the type of line, its length and the power flow. Other than changing the voltage level, the only way to regulate voltage on DC systems is to change the type of line.

Load flow feasibility ensures that a steady-state AC network solution is possible for a given topology, power injections and loads, with all components operating within their ratings. Load flow feasibility is usually validated for a wide range of operating situations as discussed further in section 4.8.3.

A power system can be said to be *stable* if the oscillatory response following a disturbance is damped and the system settles in a finite period of time into a new steady-state operating condition [8]. Usually systems are designed to withstand a range of system faults with normal or delayed fault clearing. The N-1 heuristic for stability calculations refers to the system maintaining stability after a fault with the post-fault loss of a line section as discussed in greater detail in section 4.8.4.

When designing a DC system which is integrated into an existing AC system, it is not uncommon for the HVDC link to supply a large proportion of the total system power. To limit the effect on the overall system stability due to the possible loss of a DC bipole, it may be necessary to limit the power that a DC line can carry.

Simplicity of design is concerned with the ability of the system to meet the more quantifiable criteria (operability and reliability) with a minimum degree of complexity. In other words, a system must be demonstrably operable. This is to say that it must be usually possible to meet the design criteria without recourse to extraordinary operating strategies. Such strategies should be the exception and not the rule. For example, the control of temporary overvoltages (TOV) should be inherent in the system design and not dependent on reactor switching or surge-arrester operation. In addition, the voltage profile of the system should be under automatic control that would require a minimum of switching operations of lines, reactors and capacitors for this purpose.

Finally, the reliance on special protection systems (SPS) should be limited to those extreme contingencies, such as the loss of a transmission corridor or a major substation, where the failure of the whole system is imminent. There may be some intermediate stages, such as the loss of two parallel lines, where some degree of SPS is effective but, in general, their applications should be limited. If this is not the case, then it is quite probable that the design criteria are not adequate.

Reliability is the chief attribute of a power system since it describes, both quantitatively and qualitatively, its ability to transmit power. For this reason, reliability has been described by various concepts including adequacy, security, integrity, limitation of the extent of a failure and restoration. The last three concepts analyze extreme system conditions and are concerned with the ability to control a degraded system. They are not considered in preliminary design as they require a more detailed system simulation over a period of time [24].

Adequacy is the ability to meet the load in steady-state when subjected to random outages and is a probabilistic concept which is applied to the generating and/or transmission system. *Security*, on the other hand, is a deterministic concept which defines the desired response of the system to well-defined normal and extreme contingencies as well as the actions required to maintain system integrity. These actions can vary from none at all, to specified amounts of load or generation rejection or both. The definition of these events and the corresponding permissible actions form the adequacy and security criteria [74].

The most common reliability criterion used in transmission design is the N-1 criterion which ensures that there is enough reserve capacity available through component reserve or spares to transmit full power with any one element out of service. The N-1 criterion has been used as a general design heuristic to ensure an acceptable, overall system reliability [6],[34]. A wide range of other reliability criteria may be specified pertaining to the behaviour of the magnitude, frequency of occurrence and duration of parameters such as energy or power curtailment, over/undervoltages and over/underfrequencies [24]. Frequently used criteria are loss-of-load probability (LOLP) and expected power not supplied (EPNS) [75] which are described in section 4.8.5.4.

Flexibility is particularly concerned with the ability of the proposed design to fit in with the transmission system in its present status and as it expands. This consideration will have an impact on the type of transmission (AC or DC), the choice of voltage levels, equipment ratings and the acceptable level of the technology proposed. It is important to have flexible designs, as planning decisions will affect the investment and operating costs for many years to come [41],[57]. For example a power utility, when considering the number of transmission lines to build in a corridor, could use high levels of series compensation to avoid building an additional transmission line. Although saving the utility immediate capital expenditures, the heavily loaded lines may necessitate large future expenditures, such as building an additional transmission line, for relatively small increases in the load. Had the additional transmission line been built initially, the capacity of the power system could have been increased with small amounts of series compensation.

3.4 General Design Methodology

3.4.1 Introduction

The design process is directed by the design criteria and consists of determining component combinations which best meet these criteria and the design specifications. The main specifications for preliminary design are the power and the distance over which it is to be transmitted, as well as the typical electrical, mechanical and cost component characteristics. The design variables consist of the type of transmission (AC or DC), the transmission voltage level, as well as the number and specific type of the various system components. Systems are designed to reduce overall cost and maximize system reliability. The preliminary design results should include, for each of a set of possible system designs, system topology, components, as well as system performance, including operability measures, reliability and overall cost.

Comparing AC and DC systems, the AC system tends to be more adaptable as it has a self-regulating nature with a minimum of dependency on external controls. DC systems, however, require complicated control systems and thus dictate additional economic justification for their implementation [72].

Part of system design includes identifying relevant design criteria pertinent to that particular system. For example, some systems will be stability limited whereas others will be restricted by thermal constraints. One is, therefore, forced to examine the criteria and evaluate the effect of changes in the severity of the criteria versus the benefits or penalties on cost and reliability. This balance between design criteria and reliability is achieved through sensitivity analysis [109]. It is difficult to achieve similar reliability indices for all designs and thus a cost is assigned to unsupplied energy to permit more equitable economic comparison [6].

The main steps of preliminary transmission design are shown in Figure 3.1. Initially the power system design parameters and costs are defined based on regional planning studies. The planner then estimates, based on heuristics, look-up tables or his/her experience a probable system estimate. The system is refined and modified using transmission analysis tools. If the design criteria are met for this system, then it is retained and additional designs are proposed and analyzed.

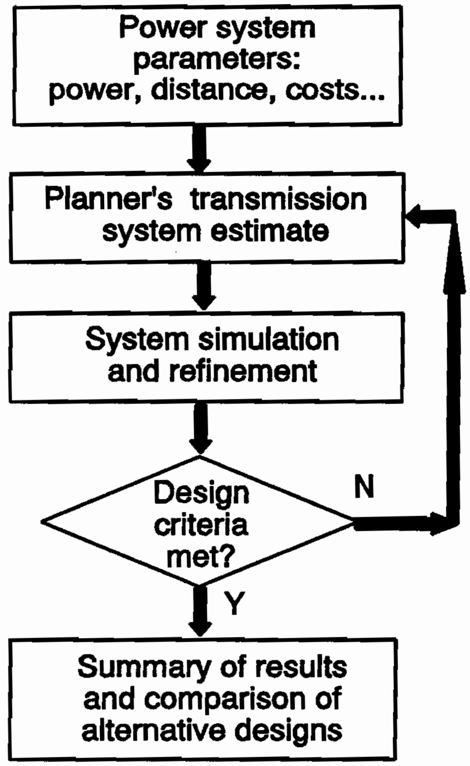


Figure 3.1: Transmission System Design

A discussion of the general AC and DC design process as well as a brief description of each of the transmission system components is provided below. The choice of AC or DC transmission is determined based on overall system comparisons such as cost, reliability, operability and flexibility.

3.4.2 General AC Design Methodology

A typical AC point-to-point transmission network shown in Figure 3.2 consists of generation, step-up and receiving transformers, intermediate substations (SS), line sections and the existing network. Each line section may have series-capacitor (SC) and shunt-inductor (SL) compensation while each substation may contain a static VAr compensator (SVC) [56]. The electrical representation of each of the system components is summarized in Table E.1.

The AC design variables consist of the transmission voltage levels, the number of circuits and type of conductors, the number of intermediate substations, the number of transformers, and the degree and type of compensation. The values of these quantities together with the corresponding system performance constitutes an AC design.

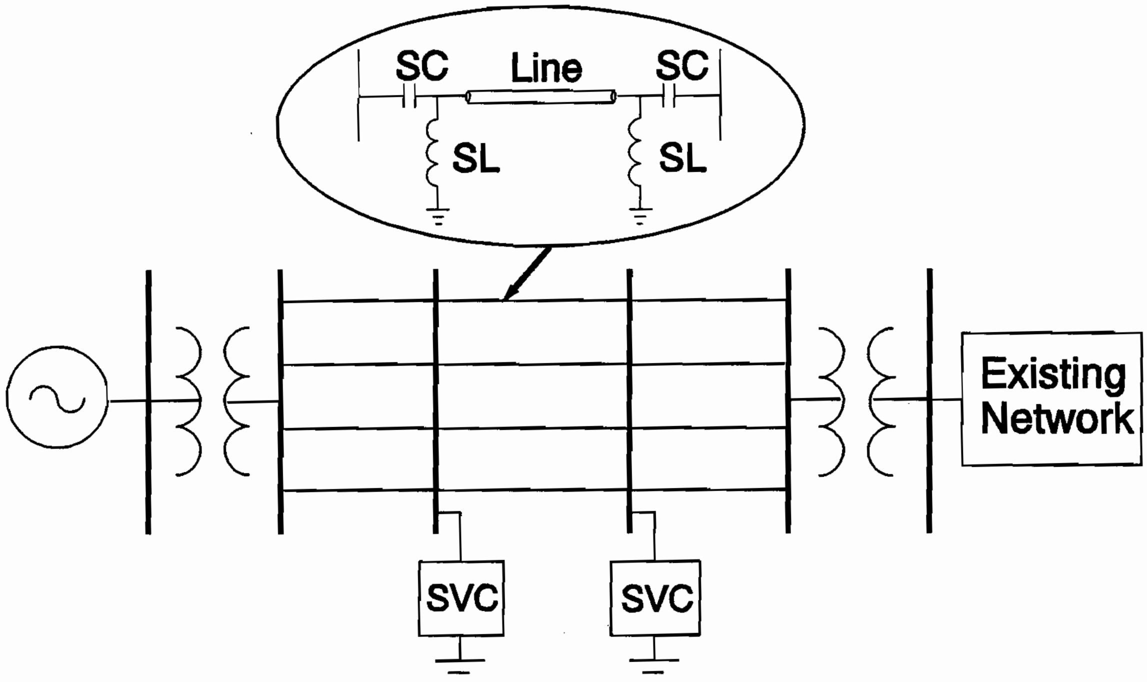


Figure 3.2: AC Point-to-Point Transmission Network

There is no explicit method for solving the transmission design problem but, in a broad sense, transmission design is a matter of reactive-power management in steady-state and during transients. The objectives of steady-state operation are to optimize the voltage profile under various loading conditions and to minimise unnecessary circulation of VArs within the system both of which favour maximum power transfer and minimum losses. Transient reactive-power management focuses on controlling overvoltages (due to switching surges and load rejection) and undervoltages (due to faults or generator tripping). Reactive-power management may, in fact, require balancing many conflicting constraints, such as stability and overvoltage, which can mainly be reconciled by a judicious mixture of series and shunt compensation and possibly some dynamic compensation as well [109].

The first step toward achieving a proper reactive-power balance is identifying reactive sources and sinks. Sources of reactive power are generating units as well as series and static VAr compensation. Reactive power may also be augmented by increasing the transmission line voltage level or the number of circuits. On the other hand, reactive power is consumed by the load and the transformers while transmission lines are either reactive sources or sinks depending on their loading [60]. Each of the AC model components are now discussed from the perspective of VAr management and system design.

Transmission lines are usually represented by a π section model as shown in Table E.1. Transmission lines are limited by thermal loading for short lines, by voltage drop for medium lines, and by stability limitations for long lines. Long transmission lines are normally loaded at or near their surge impedance loading (SIL) [59] so as to maintain a good voltage profile without excessive VAr compensation.

Transformers are represented by their leakage reactances with the magnetising current usually neglected.

Series-capacitor (SC) compensation improves the VAr balance of a transmission line by reducing the equivalent series reactance of a long transmission line. SC improves the steady-state and transient stability responses and minimizes voltage dip at load busses. Series capacitance can more than double the transient stability load limits of long lines for a substantially lower cost than the addition of new lines (see section 5.3.9). However, series compensation must be used judiciously as problems such as sub-synchronous resonance may occur in some systems [64]. This type of resonance is explicitly considered only in the detailed design as it requires the simulation of the complete system. The degree of series compensation is usually expressed as a percentage of the line reactance and ranges up to 90%.

Shunt reactors (SL) are used to balance the undesirable effects of the capacitance of high voltage transmission lines especially under light load conditions or unloaded lines during energization or load rejection [6]. Although shunt reactors can be connected to tertiary transformer windings, they are usually assumed to be connected directly to the transmission line to avoid having to add sacrificial surge arrestors to protect substation equipment in the event of load rejection. An increase in the amount of shunt reactance marginally reduces line loadability and tends to reduce system stability. The degree of shunt compensation is usually expressed as a percentage of the line susceptance ranging from 0-90% [59].

Static VAr compensators (SVC) are thyristor controlled devices which produce variable reactive power to maintain the bus voltage close to nominal [70]. SVC's improve the post-fault and during-fault voltage profile thereby making the system more stable [56].

Generators usually operate around 0.9-0.95 lagging power factor. Under light loading conditions they can absorb VArs but it is usually more efficient and economic to provide VAr absorption equipment rather than have the generator absorb reactive power [60].

A specific AC preliminary design process based on the above considerations is proposed in Chapter 4 and tested in Chapter 5.

3.4.3 General DC Design Methodology

A typical DC point-to-point transmission network is shown in Figure 3.3 consisting of generation, conversion and inversion terminals, bipolar line sections and the existing network. The electrical representation for each of the system components is summarized in Table E.2.

The DC design variables consist of the transmission voltage levels, the number of circuits and type of conductors, and the rating of the DC terminal equipment. The values

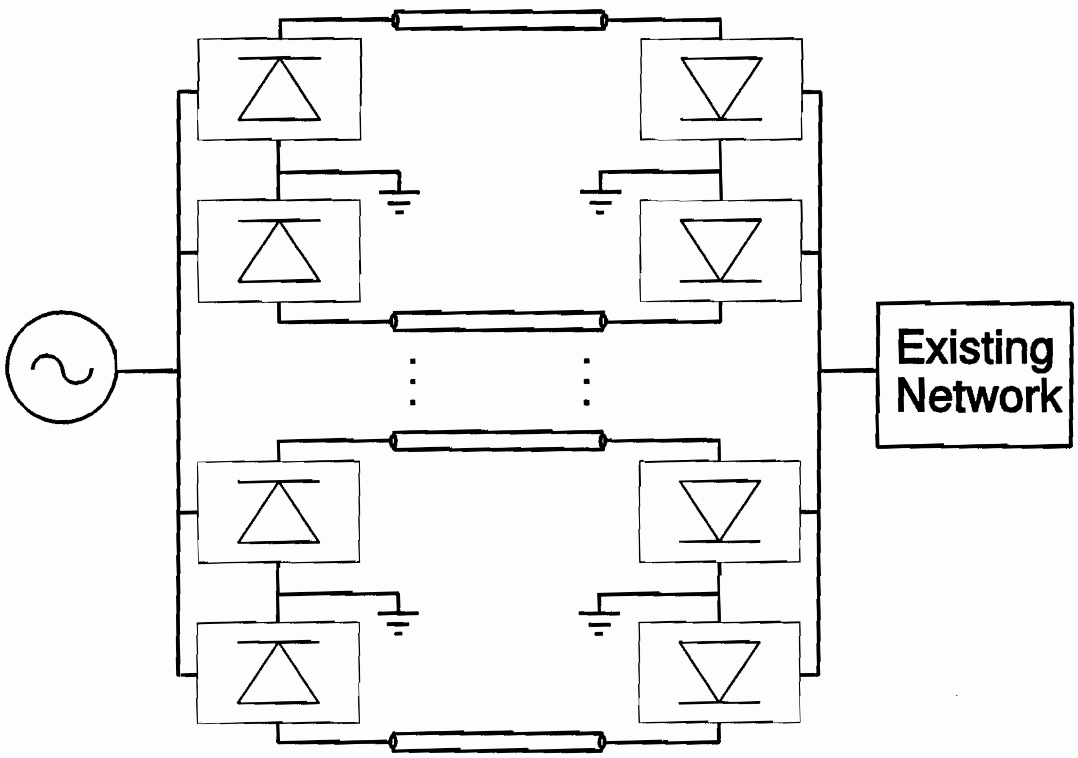


Figure 3.3: DC Point-to-Point Transmission Network

of these quantities plus the corresponding behaviour of the system constitute a DC design. The basic design methodology of DC transmission is to select a conductor size with enough ampacity to carry the load under the worst specified line or pole outage. In addition, the voltage drop and transmission losses must be acceptable under maximum load.

3.5 Summary

This chapter places the point-to-point transmission design problem within the general context of transmission planning.

The distinction between preliminary and detailed design is explained in terms of inputs, tools and results.

The methodology of transmission planning is described with particular reference to the general guidelines that govern the planning process.

Finally, a general description of the system components and the design methodology for AC and DC point-to-point transmission is presented.

CHAPTER 4

INTELLIGENT ENVIRONMENT FOR PRELIMINARY POINT-TO-POINT TRANSMISSION DESIGN

4.1 Introduction

This chapter describes an intelligent environment for preliminary transmission design based on the fundamental design methodology of expert planning engineers. To develop such an environment presupposes an in-depth understanding of the preliminary transmission design problem, as well as the design techniques and criteria required to carry out design comparisons. Chapter 3 provided the necessary basis by defining preliminary transmission planning, enumerating design criteria and design considerations as well as describing the design process. Using this framework, this chapter identifies specific modules and tasks which, when combined, form an integrated intelligent environment for preliminary transmission design called TIDE.

First, the methods used to represent transmission design knowledge are introduced followed by a brief overview of TIDE. This is followed by a summary of its development from conception to the present intelligent design environment. The structure of TIDE is subsequently discussed by identifying its various modules and their interactions. Each module focuses on one specific design problem or task and these are grouped into three categories, *Object Databases*, *Expert Systems*, and *Simulators*. Each category describes a different form of encapsulating design knowledge which, when harmoniously managed, is able to mirror a design engineer's methodology.

The final section of this chapter introduces TIDE's actual intelligent planning environment.

4.2 Knowledge Representation

It was seen in Chapter 2 that there exists a wide variety of models and tools used in transmission design and planning. Choosing the best method to represent and process design knowledge is very important as it influences not only the ability to capture and manipulate design knowledge, but also the development effort, the processing speed and the maintainability of the design environment. Traditionally design engineers relied on past experience, intuition and simple power system tools to design transmission systems.

Artificial intelligence was seen to be the best way to encapsulate the engineer's creativity and ability to reason when designing transmission systems. Artificial intelligence (AI) is a branch of computer science concerned with designing intelligent computer systems. Intelligence, in the context of AI systems, is associated with human behaviour such as reasoning, solving problems, understanding language and learning [11]. The thesis focuses on using AI tools to emulate the reasoning and solving process of design engineers in the scope of preliminary transmission system design.

Some of the related tools presently being used in AI are blackboard architecture, fuzzy logic, neural networks, case-based reasoning, frame-based representation, object-oriented programming and expert systems. These will be briefly introduced with an indication of their suitability for a transmission system design environment. The last two methods are discussed separately in the context of the three knowledge-representation methods actually used in the design environment, TIDE.

Blackboard architecture is an approach that orchestrates a cooperative solution of many different program modules and knowledge sources [49]. The blackboard consists of a database containing information common to all program modules as well as a module which schedules and coordinates the tasks of the various program modules. The blackboard is analogous to a committee of people solving a problem around a blackboard. Blackboards were not necessary for TIDE yet the concept of expert systems controlling program modules is used throughout. As additional features are added to the design environment, it can be envisioned that blackboards may be necessary in the future.

Fuzzy logic uses mathematical techniques for modelling uncertainty and is an expanded set of truth values over the interval of [0..1]. Imprecise or vague concepts are emphasised such as very or not-very hot [65]. This notion of vagueness did not readily lend itself to the scope of the numerical design criterion and the usage of power system simulators. It could be envisaged that fuzzy logic could be very useful for design comparison where system performance is more of a fuzzy concept.

Neural networks are comprised of many single elements connected in a manner inspired from biological nervous systems [78]. Neural networks are trained with sample test cases and, using the information gained, can then interpolate new outputs. They are useful for analyzing complex phenomena which do not have explicit mathematical models or when the processing speed is very important. As the fundamental design concepts of preliminary transmission systems are available from planning engineers, the actual concepts governing the design can be implemented directly.

Case-based reasoning searches a database and identifies similar cases, the solutions of which are then modified to approximate the results of the actual problem being considered [108]. For similar reasons to neural networks, case-base reasoning was not considered in TIDE.

Frame-based representation is a structure which enables data objects to be represented using a data structure. Objects have attributes in which the values of these specific properties are placed. Frames often enable a hierarchical structuring of objects and classes which permits values to be inherited [3]. Frames are used extensively in the TIDE design environment to enable rules to reason over many objects. Frames are very valuable for the proposed design environment but are enhanced to include the functionality of object-oriented databases.

Having introduced various techniques available to represent design expertise, all the methods which are actually used in TIDE are now discussed. Transmission design is a complex, multifaceted process requiring not only an designer's experience but also data storage and power system simulation tools. Thus, a hybrid of three methods, each performing a well-suited task, is seen as the best solution in developing a transmission design tool. The methods or categories used to represent the knowledge necessary for this work are object-oriented databases, rule-based expert systems and sequential or conventional techniques which are in nature structural, heuristic and procedural/algorithmic respectively. The criteria used to allocate certain tasks to each type of knowledge representation is described below.

Object-oriented programming is a data driven programming method where procedures are associated with objects. Object-oriented programming encourages modularity where object properties and methods are hidden within the object. Objects communicate with each other through the use of messages. Often times, object-oriented environments are capable of representing knowledge in a manner similar to the frame-based representation where attributes and methods are inherited [91]. Such an environment is used for this research. Although object-oriented databases permit method inheritance, the concept of modularity, however, is not retained as the object properties are readily accessible by all other objects.

Object-oriented databases force and exploit inherent data structures which associate methods and values with objects. These methods are data driven and permit knowledge to be reused on various levels. The drawback of this generalization is in representing exceptions to the data structure and the penalty of slower data access times which did not pose a problem for this work.

Expert systems are intelligent computer programs which use knowledge and inference procedures to manipulate concepts that would normally require significant levels of human expertise. They are well suited to solving problems that are heuristic in nature and manipulating concepts which are not readily handled by conventional programming methods [91]. One of the key differences between expert systems and conventional programming is the expert system's separation of the domain knowledge from the actual knowledge processing or inferencing. Conventional programs frequently mix the two throughout the program whereas expert systems attempt to make a clear separation and rely on generic inference mechanisms to reason with the knowledge.

The strength of expert systems lies in their ability to parallel an expert's reasoning methodology, to represent generalized heuristics, to dynamically process the flow of logic and to explain its reasoning [48]. The weaknesses of expert systems are the difficulty in representing readily comprehensible knowledge, the possible unanticipated knowledge processing, slow processing speed due to interpreted rules, difficulty in representing numerical algorithms and the difficulty in ensuring that the knowledge is complete and accurate [54]. Many of these problems were overcome by creating separate expert system modules as well as using a hybrid of various tools.

Expert systems have been in use for numerous power system applications some of which are summarized in references [28] and [36].

Sequential methods are the oldest and most prevalent type of knowledge representation. The tools presently available, such as FORTRAN, Basic and C, are mature and well suited for implementing algorithms. As their order of execution is predictable, proof of optimality and convergence is greatly facilitated. Their weaknesses lie in representing and manipulating concepts or ideas which are not sequential in nature.

Object-oriented databases, expert systems and sequential programming each have their strengths and weaknesses. By creating a hybrid environment comprised of all three, the strengths of all the methods can be exploited.

The previously outlined separation of knowledge is not so evident when developing an actual hybrid system. There always exists a tension among the methods used to represent the knowledge. The choice to use a less than ideal environment for certain operations is determined based on the "distance" between the available tools used to perform the task. For example, when developing simulators which used sequential algorithms, an expert system would ideally control their processing method but this is not always possible. Efficiency may require that some expertise, represented in a normal sequential programming manner, be imbedded inside the simulators. The overall objective still remains to use the best suited tool for the task to facilitate design expertise retention.

4.3 Overview of TIDE

An overview of the main transmission system design methodology of TIDE is summarized in Figure 4.1. The main design inputs are distance and power. TIDE then generates preliminary AC or DC designs using heuristic rules which determine appropriate voltage levels and number of transmission lines. Additionally, for AC systems, the number of intermediate substations and compensation levels are also estimated. These designs are then refined to meet system criteria while, at the same time, respecting normal operational practices. The reliability of the system is then determined by considering degraded system states. Suggestions are then made to improve the system reliability by installing additional spare components. Based on the cost-reliability results, other designs are then suggested by the expert system to search for superior designs. Finally, a reduced list of feasible transmission systems and their performance measures are submitted as an output to the planner.

4.4 History of TIDE

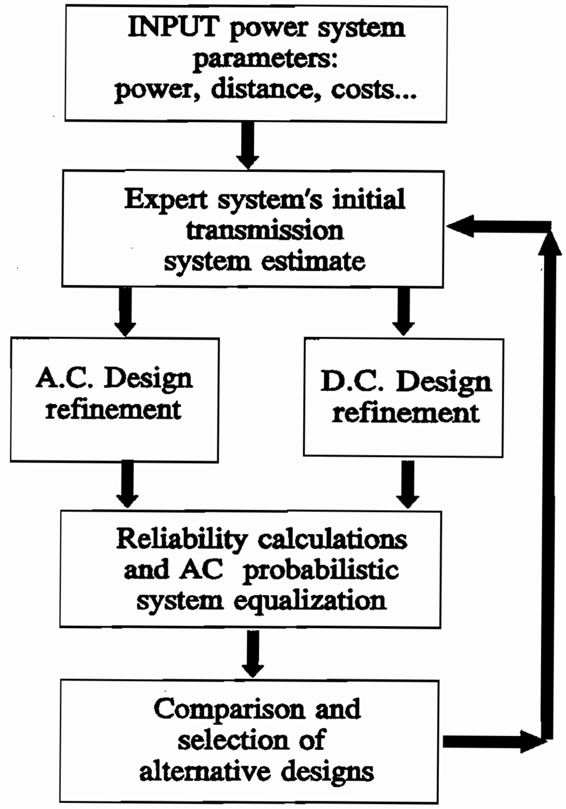


Figure 4.1: Design Methodology in TIDE

TIDE (Transmission Intelligent Design Environment) is an intelligent system for the preliminary design of point-to-point power transmission networks which has evolved considerably over the past eight years. A precursor to TIDE, named TRANSEPT, was developed through the collaboration of McGill University and Hydro-Québec [38] which provided the expertise of a number engineers. Since 1991, TIDE has been developed by McGill University and several independent power system experts [84] through extensive additions and innovations in the knowledge base, man-machine interface (MMI) and integrated simulation tools. The main goal of this work has been the development of an integrated package of expert system modules covering the main facets of preliminary transmission planning. This project is far from static and is ever expanding in available features, capabilities and depth of understanding but the principal concepts and software form the basis of this thesis. A summary of the developmental stages of TIDE is shown in Table 4.1.

TRANSEPT was initiated in 1988 by D.T. McGillis of Hydro-Québec as the main domain expert and by F.D. Galiana of McGill University as the knowledge engineer [37]. They were joined later that year by J.-P. Bernard of McGill University as a knowledge engineer and programmer. Project management was provided by R. Manoliu of Hydro-Québec.

Table 4.1: Stages of TIDE Development.

Date/ References	Additional Features	Reasons / Changes	
1988,[37]	Prototype		TRANSEPT
1988-1989 [46],[86]	Platform Change: Goldworks to Nexpert	-Complications with external simulator access -Isolated LISP mathematical environment -Availability of improved expert system shell	
1988-90 [38]	Parametrize Variables	-Increase generality and flexibility of TIDE	
1989 [42]	Insulation Coordination	-Additional design considerations	
1990,[100]	DC Analysis	-Consider the other main type of power transmission	
1991 [46]	Combined AC/DC	-Consistent structure and methodology -Improve comparison of alternatives -Centralized database access	
1991-92 [67],[66]	AC Reliability	-Additional cost for comparison -Improve comparison of alternatives -Closer matching of existing criterion	TIDE
1992 [68]	Automated Search	-Ensure optimality -Ability to automate testing of TIDE	
1992 [41]	Power-Distance Table	-Validation of TIDE -Increase scope	
1993	Generalized Parametric Studies	-Enable in-depth sensitivity studies of design parameters and component values	
1994 [87]	Transmission Tower Design	-Improve line cost accuracy	FUTURE
Future Research [9]	Substation Design	-Provide electrical characteristics for the substation components for TIDE	
Future Research [26]	Interconnection Design	-Expand design capabilities	
Future Research	Learning	-Improve performance of TIDE -Enable TIDE to learn from the knowledge inherent in its structure	

The first TRANSEPT prototype for the design of AC-transmission networks was completed by the end of 1988 [39]. It was written using Goldworks, an expert system development shell based on LISP [3]. During 1989 and 1990 TRANSEPT was tested by design engineers in Hydro-Québec and some recommended improvements were implemented, of which the main ones consisted of parameterizing many design variables thereby generalizing the design process [38]. This ability of the expert system has proven extremely fortuitous, particularly with respect to design criteria since the concept of criteria governs the coordination of all the main ingredients that make up the design of the transmission system.

It was decided at this stage to change the basic programming environment from Goldworks, a LISP-based shell, to the faster and less memory-intensive Nexpert Object shell based on the C language [46],[86]. New modules were subsequently developed for the design of insulation coordination [42], for DC-transmission [100] and transmission line design [87].

In 1991, the development of TIDE began with the objective of explicitly incorporating reliability and parameter sensitivity considerations into the design knowledge base, developing and integrating several analysis and simulation tools, and supplying everything with an advanced MMI. This required a major restructuring of the entire package both from the conceptual and the programming perspectives.

Expert systems are characterized by an iterative process in the progression from inception to the realization of a system that is of practical use. As the expert system's capabilities increase, it outgrows its initial formulation and environment and thus requires restructuring. TIDE is no exception and has gone through many restructuring iterations as more features and knowledge were incorporated into this planning tool.

4.5 Structure of TIDE

The knowledge base of TIDE, its heart and soul, is represented using object databases, expert systems modules and simulators. TIDE processes this knowledge and infers results in the form of new transmission designs meeting all design criteria and constraints at low cost. Several complementary knowledge modelling techniques are used to encapsulate the design expertise of TIDE. Since there needs to be harmony among all categories of knowledge and modules comprising the expert system, it is necessary for these to exploit their intrinsic abilities in an efficient, well structured manner.

Each of the three categories of TIDE knowledge namely, object databases, expert system rules and simulators, is comprised of separate modules, each performing a specific task. The overall structure of TIDE is shown in Figure 4.2. The object-database category contains data about Equipment, Design expertise, Design criteria, Transmission systems, and Housekeeping. The expert system modules category consists of Design, Simulator control, Costing, Search strategy, Menu control and Database validation modules. Finally, the simulator category has Voltage control, Load flow, Transient stability and Reliability modules.

The *exchange of knowledge* among the various modules is represented pictorially in Figure 4.2 and a typical design session will now be described in general terms:

- Using the menu driven interface, the user inputs, retrieves or modifies AC and DC transmission equipment and design criteria.
- The Database validation module ensures data consistency and reasonableness.
- The Menu control rules, accessing the Housekeeping module, allow the user to move through various input, output and summary menus.

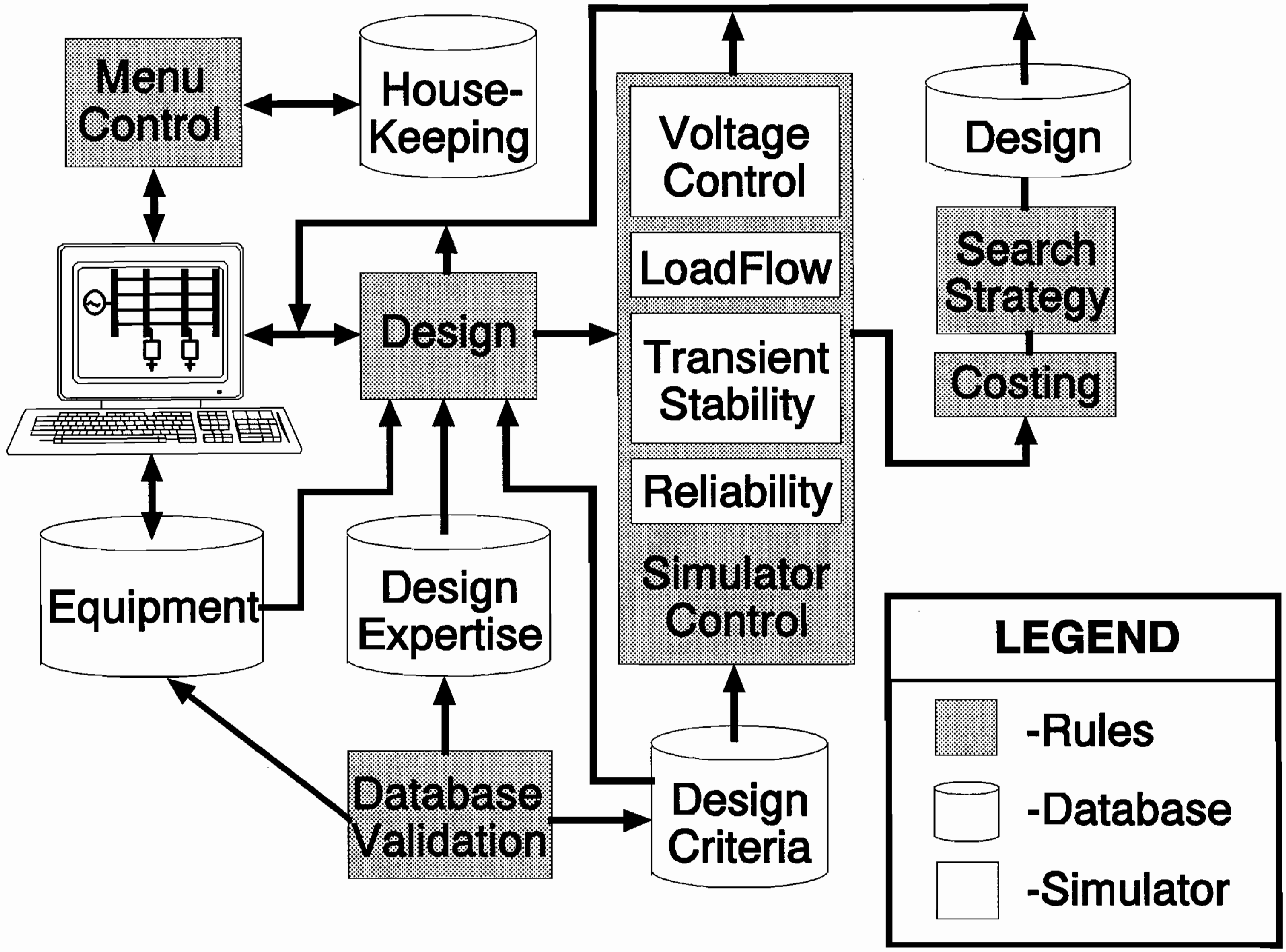


Figure 4.2: Structure of TIDE

- Skeleton structures of AC or DC transmission systems are then determined by the Design module using the Design expertise module for the desired power and distance. For AC systems, the Simulator control module, manipulates the Voltage profile, Load flow, Transient stability and Reliability simulators while, intelligently refining the compensation levels and spare components to ensure that the design criteria are met. For DC systems, the Design module matches equipment and design criteria. Feasible AC and DC designs are then costed and ranked.

- The Search strategy module then suggests alternative designs according to a set of heuristic rules.

- Finally the results are presented in a manner to help the planner compare quantitatively the proposed system designs according to a broad set of criteria.

Each knowledge category and corresponding modules are now discussed in more detail in sections 4.6-4.8.

4.6 Object Databases in TIDE

4.6.1 Introduction

A database is a collection of objects interrelated according to some structure. TIDE's data structure, using Nexpert Object, is hierarchical in nature, consisting of classes, objects, properties and slots. *Classes* are templates that define characteristics that its members (objects or other classes) possess. These characteristics can be structural (class hierarchy), inherited properties, default property values or methods. *Objects* are specific instances of classes inheriting class properties and may be either persistent or dynamic. Dynamic objects may be created or destroyed whereas persistent objects are retained throughout the operation of the expert system. *Properties* are the specific characteristics of a class or of an object and *slots* are particular values of these properties [3],[5].

An example (Figure 4.3) of the above structure is the *class* of transmission lines characterized by general *properties* such as voltage or impedance. An *object* belonging to this class is a specific transmission line, (e.g. line from station X to Y), inheriting the properties of the parent class. The specific *slot* or property values of the properties might be voltage = 735 kV, reactance = 330 mΩ/km. Similarly, a *method* can be associated with a property such as impedance which could recalculate the line's surge impedance loading (SIL) if and when the impedance's slot value is changed.

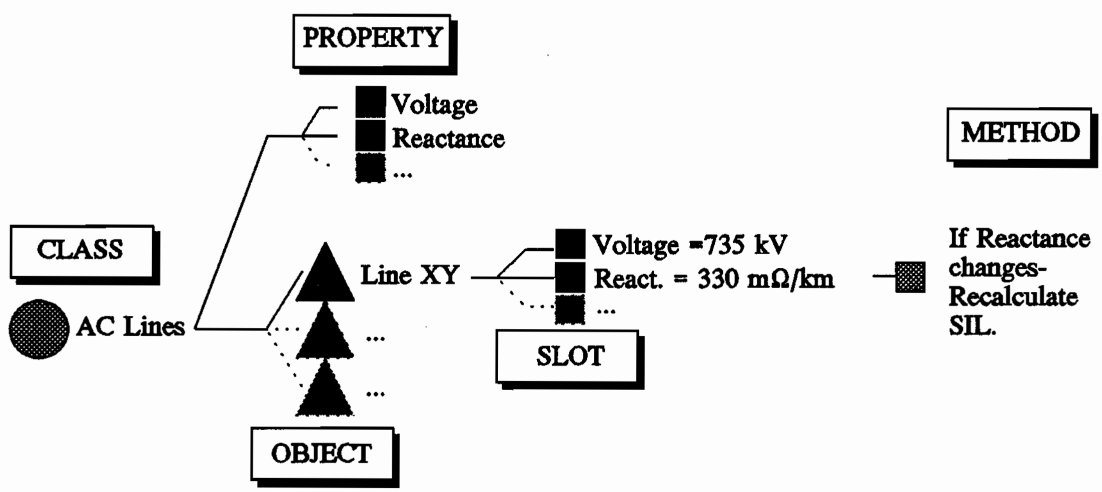


Figure 4.3: Object Database Example

The database structure of TIDE is divided into five main database modules: Equipment, Design criteria, Design expertise, Housekeeping and Transmission systems. A brief description of each module as well as the usage of the database's structure is discussed in the following sections and summarized in Table 4.2. In all, there are 64 classes, 366 permanent objects and 261 properties (since some objects may share the same property) in TIDE. In particular, the Equipment database contains 56 dynamic objects and,

Table 4.2: Database Specifications Summary

Database Name	Description	Usage of Structure		
		Classes	Inheritance	Dynamic Objects
Equipment	Contains details describing specific equipment attributes.	Three levels: All equipment, AC or DC equipment, and the actual devices	Default values and validation methods.	Fixed class structure and dynamic device objects.
Design Criteria	Contains limits and ranges that a prospective design must meet.	Various single level classes.	Default values.	Fixed class and object structure.
Design Expertise	Contains recommended amounts or values of different attributes of a power system design.	Various single level classes.	Default values and validation methods when expertise is updated.	Fixed class structure with dynamic objects.
Transmission Systems	Contains specifications and simulation results of transmission systems	Single level class	Default values and methods	Fixed class structure with dynamic objects.
House-keeping	Contains information necessary for the menus and saving or retrieving design sessions.	Various multilevel classes.	Default values and methods	Fixed class structure with dynamic objects for a variety of purposes.

depending on the design options chosen, hundreds of additional dynamic objects may be created during a design session.

4.6.2 Selection of a Database Software Tool

The database tool used for TIDE is part of the Nexpert Object expert system shell [5] and has the following features: hierarchical structure, inheritance, dynamic objects, and a close link to the expert system itself. The hierarchical database structure enables reasoning at a higher level of abstraction, rule generalization and the reuse of knowledge in the expert system rule base. Inheritance permits the reuse of methods and provides default methods and values. The dynamic feature provides the ability to create, clone and delete objects and facilitates sensitivity studies and the management of the Equipment database. The close relationship between the expert system and the database enables data changes to start an inferencing process to validate input variables. All of these features aid in the development of a concise, well structured expert system. It was not necessary to access external databases as the database functions of Nexpert Object have sufficient power and the necessary capabilities required by TIDE. It is, however, necessary to transfer data between the simulators and the expert system shell. The simplest method of using files is chosen for this purpose even though direct queries could be realized. Data sets are also stored in files for subsequent retrieval into the database.

4.6.3 Equipment Database Module

The Equipment database catalogues the various transmission system components described in Table 3.3. These components consist of generators, transformers, DC terminals, transmission lines, series capacitors, shunt reactors, static compensators, substations and load.

The parent class of the Equipment database describes general properties common to both AC and DC equipment. More specific properties are then added to the subclasses ac_equipment and dc_equipment and finally to the component classes such as lines, transformers, compensation as shown in Figure 4.4. Thus, descending the class structure,

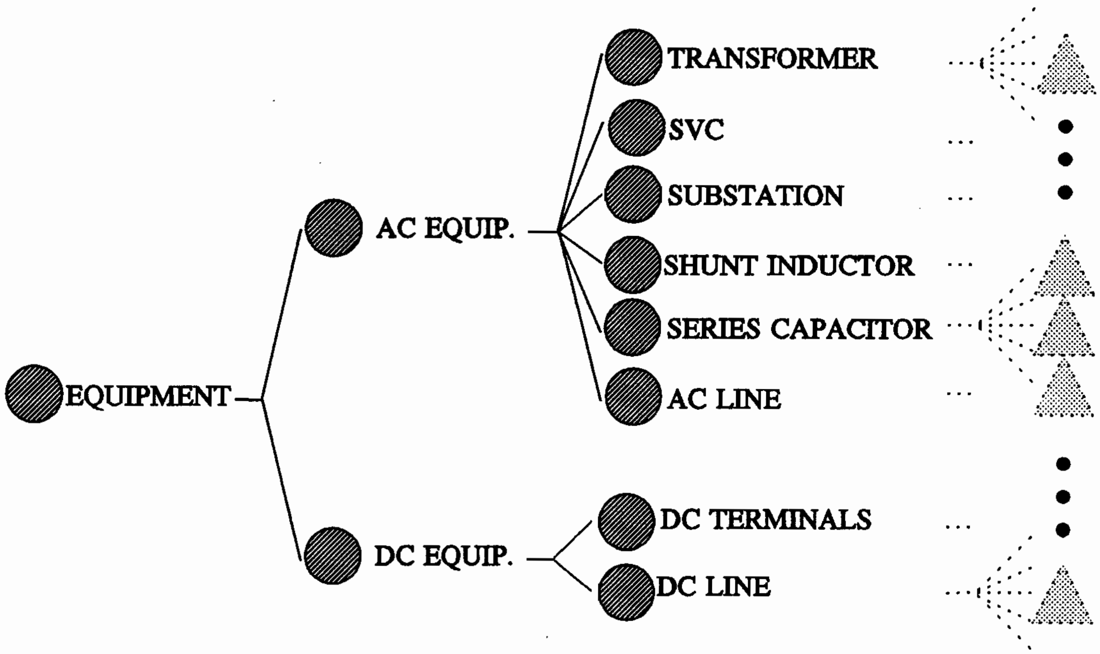


Figure 4.4: Equipment Database Overview

the representation becomes increasingly more detailed until the complete component representation is obtained. Typical equipment specifications are described in Appendix B. Inherited methods of this class structure validate data changes and determine values for unknown slots. The Database validation expert system is described in further detail in section 4.7.8.

4.6.4 Design Criteria Database Module

The various design criteria, summarized in Table 3.4, specify the prescribed performance of the system reflecting physical component limitations as well as ensuring proper network operation. This database holds these various design criteria and has no inherent structure to it as the criteria are unrelated. The design criteria are specified by the user although default values are provided. This data is used by the Design and Simulator control expert system modules. (See section B.2).

4.6.5 Design Expertise Database Module

The Design expertise database consists of the parameters used by the expert system to define and execute the design rules. While the rules themselves cannot be changed, the parameters can be altered by expert users to adapt the expert system to particular environments. An example of expertise data is shown in Table 4.3 where typical voltage levels are provided for ranges of power and distance. Other design expertise data include such items as recommended distances between AC substations, suggested voltage levels for DC systems and maximum power loss as a function of power for DC converters. These are shown in Appendix B.

Table 4.3: Voltage Design Expertise Data Table [38].

Power Range (GW)	Distance Range (km)			
	[0,250)	[250,750)	[750,1250)	[1250,∞)
[0,2)	315kV- 315kV	315kV- 500kV	500kV- 735kV	735kV- 735kV
[2,8)	315kV- 500kV	315kV- 500kV	500kV- 735kV	735kV-1200kV
[8,16)	500kV- 735kV	500kV- 735kV	735kV-1200kV	1200kV-1200kV
[16,∞)	735kV- 735kV	735kV-1200kV	1200kV-1200kV	1200kV-1200kV

4.6.6 Transmission System Database Module

The Transmission system database module contains all the design parameters, cost and performance of each preliminary transmission design. The performance and cost include:

- losses
- temporary overvoltages (TOV)

- VAr requirements of the generation and static VAr compensators in light and heavy loading conditions
- VAr requirements of the generation and static VAr compensators during transients
- system voltage angles for steady-state and transient conditions
- reliability (LOLP and EPNS values and states)
- overall system cost and cost breakdowns into components, losses and unreliability.

The cost and performance is presented to the user in summary tables and may subsequently be used for sensitivity studies. The reader is referred to Chapter 5 and Appendix A for sample performance and cost tables.

4.6.7 Housekeeping Database Module

The Housekeeping portion integrates the Database validation and Menu control, data input/output and Simulator control. This database contains all the information necessary to achieve an operational design environment such as the data structure to communicate with the simulators, or saving and retrieving previous design sessions.

4.6.8 Summary

The different levels of the hierarchical database in TIDE permit reasoning from the particular to the general such as from an individual line to all the lines, or to all the AC equipment, or to all the transmission equipment. This ability to group objects enables knowledge to be reused efficiently throughout the database.

4.7 Expert Systems in TIDE

4.7.1 Introduction

The expert system category of TIDE consists of various modules, each one performing a specific task in the design process which is usually heuristic in nature and can readily be captured in expert system rules.

Rules are part of the domain knowledge expressed in condition-action statements stored in the knowledge base. A rule has two parts. The first part is a condition clause which, if verified, proceeds to the second part which consists of action clauses. A rule is identified by a boolean hypothesis indicating whether it has been fired [55].

An example of such a rule would be:

If a system is unstable and the series compensation has reached its maximum allowable level then add static VAr compensation.

Rules are fired when their knowledge is necessary in the flow of reasoning and the knowledge required to trigger these rules is available. The rules are fired by the inference engine in either a forward-(data driven) or backward-(goal driven) chaining mode. Rules may also be triggered by changes in the database. Forward-chaining uses suggested data to conclude new results. Backward chaining attempts to instantiate an hypothesis by determining if there is sufficient evidence to verify it [5].

An overview of the characteristics of the expert system modules used in TIDE are summarized in Table 4.4 where the size (number of rules), processing method (chaining type) and structural depth for each module is provided. A link is also made between the

Table 4.4: TIDE Knowledge Base Specifications Summary

Expert System Name	Description	Number of Rules	Chaining		Usage of Structure		
			Type	Depth	Database Modules	Inheritance	Dynamic Objects
Design	Determines initial system designs.	34 AC 18 DC	Backward	8 7	Equipment, design criteria & expertise	Methods & default values	New designs
Simulator Control	Imbedded expertise in simulator.	-	Sequential	-	-	-	-
Costing	Determines costs of designs using formula.	9 AC 5 DC	Forward	1	Transmission systems	Costing methods	-
Search Strategies	Looping to control design search area.	4	Backward	4	Transmission systems	Initial values	New designs
Menu Control	Setup data for menu access and control.	8	Backward	1	Menu structure	Methods & default values	-
Database	Ensure database consistency and reasonableness. Enables modifying groups of data.	114	Backward	4	All databases	Validation methods and tolerances	-

object databases and the expert system modules indicating which database modules are used in the rules and the inheritance strategies provided as well as the dynamic objects created by these expert systems.

From Table 4.4 in TIDE it can be seen that backward chaining is the predominant method of processing rules. The levels of reasoning in the various rule structures vary in depth from one to eight depending on the context. The Design and Search strategy modules create new objects whereas the remaining modules provide values to the properties of existing objects.

Of the seven expert system modules in TIDE, Design, Simulator control, Costing and Search strategy comprise the bulk of the expert system rules and perform the main tasks for preliminary transmission design. There is, however, a certain amount of infrastructure required to make TIDE operational and robust. These remaining modules are Menu control and Database rules.

4.7.2 Selection of the Expert System Software Tools

In designing TIDE, the following main features were considered desirable: integrated database, sophisticated and high-speed inferencing process, interaction with algorithmic simulation programs, user friendliness and explanations, PC-DOS-based and a graphical design environment.

Looking at the hybrid tools which were on the marketplace in 1989/1990, the following candidates were available: ART, Knowledge Kraft, KEE, Nexpert Object and Level 5. The first screening eliminated the tools which were not PC based. ART, KEE and Knowledge Kraft were, at the start of this project, in this category.

NEXPERT Object was selected as the more appropriate tool for the following reasons: it possessed the capability to process complex rules, backward and forward chaining, as well as classes and objects. Furthermore, NEXPERT Object was able to interact with algorithmic programs, like C, BASIC and Fortran, which was an essential feature for TIDE to be able to run the required simulations. Being written in C, NEXPERT Object gives a satisfactory speed of the inferencing process [40].

Finally, NEXPERT Object is an user-friendly tool permitting the user to visualize the reasoning process and to manipulate both input data and output results on the computer screen.

4.7.3 Design Module

Design rules determine skeleton structures for AC and DC transmission systems by estimating reasonable system topologies and parameters. For AC systems these parameters include voltage levels, number of circuits, number of substations and degrees of compensation and for DC systems the parameters are voltage levels, number of terminals and circuits. These heuristic rules generate approximate designs based on basic power system formulae and design expertise. The rules are derived from well-established theories with certain simplifications and approximations, and are summarized in Table 4.5 and Table 4.6. Further details of the design rules are contained in Appendix D.

Recommended nominal voltage levels for a given power and distance are obtained based on design experience and are stored in the Design expertise database. Typical values are shown in Table 4.3 and Table B.14 for the AC and DC systems respectively.

For AC systems the recommended number of circuits is based on the transmitted power, distance, surge impedance loading (SIL) and a given maximum angle across the system. The number of substations is estimated from a recommended distance between substations. Series capacitor and shunt reactor compensation levels are estimated to maintain an acceptable temporary overvoltage (TOV). All equipment types for a specific voltage level are considered in each design. As initial system designs are estimated based on heuristics, a sensitivity analysis is also performed around the base designs. A subse-

Table 4.5: AC Transmission Design Parameters Control.

AC Design Parameter	Initial Estimate: Method	Initial Estimate: Equation	Control	Bound
Voltage	Heuristic	Lookup table	Characteristics of designs	-Number of voltage levels -Search space
Number of Circuits	Long Transmission Line approx.	$\frac{P_{max} \sin(\beta l_{eq})}{SIL \sin(\theta_{max})}$	Characteristics of designs	-Search space -Reliability
Number of Substations	Heuristic	$\frac{l}{sugg.\ dist.\ between\ SS}$	Characteristics of designs	-Maximum distance between SS -Search Space
Series Compensation	Limit TOV, VAr balance	$1 - \frac{\cos^{-1}\left(TOV_{max}^{-1}\right)}{\beta l}$	Design Criteria	-Maximum user input
Shunt Compensation	Limit TOV, VAr balance	$1 - \frac{\cos^{-1}\left(TOV_{max}^{-1}\right)}{\beta l}$	Design Criteria	-Maximum user input

P_{max}: Maximum transmitted power in MW, $\beta = 2 \pi f / 300{,}000$ in km^{-1}, f: system frequency in Hz,
l: Line length in km, l_{eq}: Equivalent line length in km (shortened by the series capacitance),
SIL: Surge impedance loading in MW, θ_{max}: Maximum angle across the system, SS: substation,
TOV_{max}: Prescribed maximum temporary overvoltage in per unit based on load rejection.

Table 4.6: DC Transmission Design Parameters Control.

DC Design Parameter	Initial Estimate		Control	Bound
	Method	Equation		
Voltage	Heuristic	Lookup table	Characteristics of designs	-Number of voltage levels -Search space
Number of Terminals	Maximum loading	$\frac{P_{\max}}{P_{term_{\max}}}$	Characteristics of designs	-Reliability
Number of Circuits	Maximum rating	$\frac{P_{\max}}{2\ V\ I_{cond_{\max}}\ n_{cbdl}}$	Characteristics of designs	-Reliability
	Voltage regulation	$\frac{P_{\max}\ r_{DC}\ l}{2\ V\ n_{cbdl}\ \Delta V}$		

$P_{\max}$: Maximum transmitted power in MW, $P_{term_{\max}}$: Maximum terminal power in MW

V: Nominal pole to ground voltage in kV, $I_{cond_{\max}}$: Maximum current rating per conductor in kA

n_{cbdl}: Number of conductors per bundle, r_{DC}: Resistance in Ω/km/conductor

l : Overall line length in km, ΔV: Maximum voltage regulation in kV, quent guided search is therefore carried out by the search rules which are described in 4.7.6.

For DC systems the recommended number of terminals/bipolar circuits is based on terminal and line capacities, voltage regulation and reliability constraints. The number of parallel circuits is bounded by reliability constraints based on the amount of power that can be lost without affecting the rest of the connected AC system for the loss of n_{rel_out} poles. The reliability can be handled in three different ways, ignored, terminal overrating and increasing the number of bipolar/terminal circuits. All equipment types for a specific voltage level are considered in each design. Additional voltage levels are considered about the estimated based voltage level.

4.7.4 Simulator Control Module

Simulator control rules control the power system analysis simulators and ensure that design criteria are met. These rules are imbedded in the simulators to improve design efficiency as many iterations are required to tune the compensation of an initial design. Simulator control rules are discussed further in section 4.8.

4.7.5 Costing Module

The costing rules determine the total cost of each transmission system. Total costs are based on the capital costs of each component and the overall system losses. The latter, normally a variable cost, are converted to an equivalent generation capital cost. The costing methods for each type of equipment are summarized in Table 4.7 [53]. More details about the costing formula are shown in Appendix F.

Component costs vary with respect to voltage and rating depending on the type of equipment. An example of a component cost is a transmission line which is costed by its two main characteristics, the number and type of conductors and the length of the line. Costs such as transportation costs, economies of scale, interest during construction and

Table 4.7: Equipment Component Costing Methods.

Equipment Component	Cost Based On:		Additional Costs: Equipment	Additional Costs: Reliability	Cost Calculation
Generation	-Power	\$/MW	-	-	$P_{\max} C_{gen}$
Transformer	-Voltage -Rating	\$/MVA	Auxiliary Equipment	Spares	$2\ n_{tsf}\ S_{tsf}\ (C_{tsf} + C_{aux})$
DC Terminal	-Voltage -Power	\$/MW	-	-	$2\ n_{term}\ C_{term}$
Transmission Lines	-Voltage -# cir. -Length	\$/km	-	-	$n_{cir}\ l\ C_{cir}$
Series Capacitors	-Rating	\$/kVA	-	-	$Q_{sc}\ C_{sc}$
Shunt Reactors	-Voltage -Rating	\$/kVA	-	-	$Q_{sl}\ C_{sl}$
Static VAr compensation	-Voltage -Rating	\$/kVA	Transformer	Spares	$(Q_{SVC_{\max}} + Q_{SVC_{\min}})\ C_{SVC} + Q_{SVC_{\max}} C_{SVC_{tsf}}$
Substation	-Voltage -# SS -# cir.	\$/cir	-	-	$2\ n_{cir}\ (n_{ss} + 1)\ C_{SS}$
Losses	-Losses	\$/MW	-	-	$P_{loss}\ C_{gen}$
Reliability	-EPNS	\$/MW	-	-	$EPNS\ C_{EPNS}$

SYMBOLS: aux=auxiliary, cir=circuit, C=cost, EPNS=expected power not supplied, gen=generation, l=line length, n=number, P=real power, Q=reactive power, S=power, sc=series capacitor, sl=shunt inductor, SS=substation, SVC=static VAr compensator, term=terminal, tsf=transformer.
(See Appendix F for the costing formulae details).

inflation are not explicitly considered in the Costing rules but may be factored into component capital costs [104].

When power system reliability is evaluated (see section 4.8.5), the overall system cost also includes the cost of the expected unserviced power due to system unreliability [6]. If the Reliability module adds spare components, these are also included in the system costs.

4.7.6 Search Strategies Module

Planning experts are able to limit the feasible search space by relying on previous experience. Paralleling this expertise, heuristic design rules determine likely, although not necessarily optimal, transmission designs. (See Figure 4.5). Search strategy rules extend the design space to ensure that the least expensive preliminary transmission design is considered.

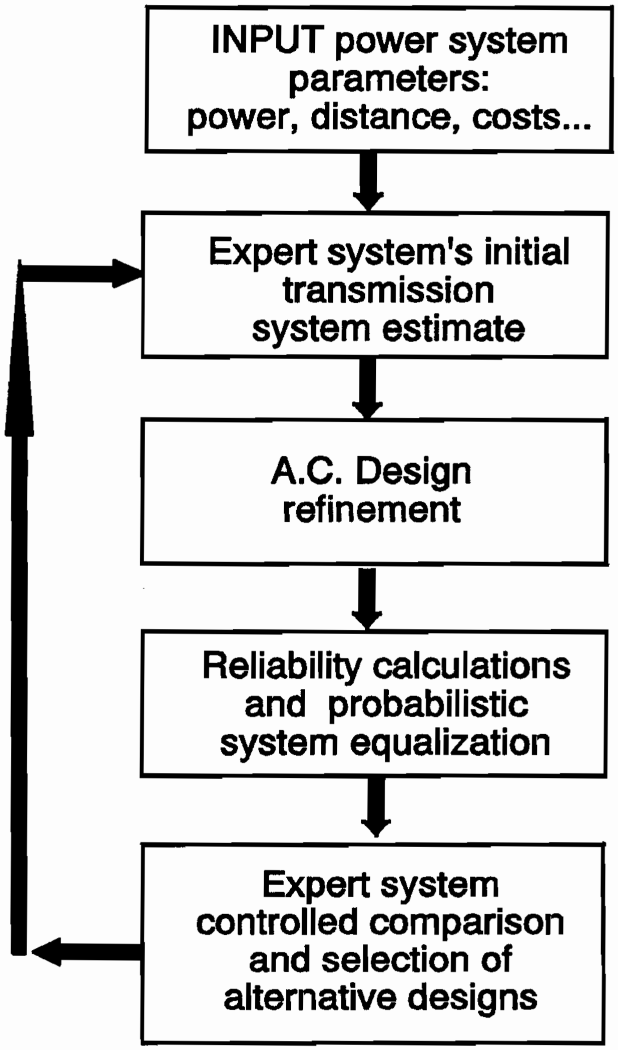


Figure 4.5: Expert System Controlled Search.

The Search strategy considers the following parameters: voltage level, number of circuits and the number of substations. The remaining system parameters are governed by the control module (see section 4.7.4) which ensures that the design criteria are met. The search rules perform a sensitivity analysis about the original search region specified by the Design module. The search criterion is based on the total system cost (see section 4.7.5) and is non-monotonic due to the nonlinear response of the power system and to the fact that components are added in discrete steps. To obtain an optimal solution, the search space must be sufficiently large so as not to be influenced by local minima. The search is bounded by reliability criteria, (EPNS, LOLP, minimum number of circuits), available equipment and accepted robust design practices. Any system not meeting these criteria is rejected unless it can be modified and improved by the control module through the simulators.

An example of the system search is shown in Figure 4.6. The initial expert system has three intermediate substations and three circuits. The search space is bounded by the input criteria of a minimum of two circuits and one substation. A sensitivity analysis of ± 1 substation and ± 1 circuit is performed about the expert system's initial estimate for this particular voltage level. The least-cost design is on the border of the search area and so the search is extended, denoted by the cross-hatched lines in the figure. The search process is repeated until the least-cost solution is at the centre of the sensitivity region or is bounded by the constraints. The search procedure can be repeated for various voltage levels as well.

4.7.7 Menu Control Module

Menu control rules govern the interface between the user and the expert system, warn the user of problems that the expert system encounters and provide help screens and explanations of the expert system methodology. The advantages of having expert system controlled menus is the simplicity and ease of implementation. Menu access is controlled by rules reasoning on objects in the Housekeeping database and in the menu definition files. It is possible to easily add new menus or modify existing ones through the Menu control module rules. This feature is very useful during the development stage of a tool like TIDE.

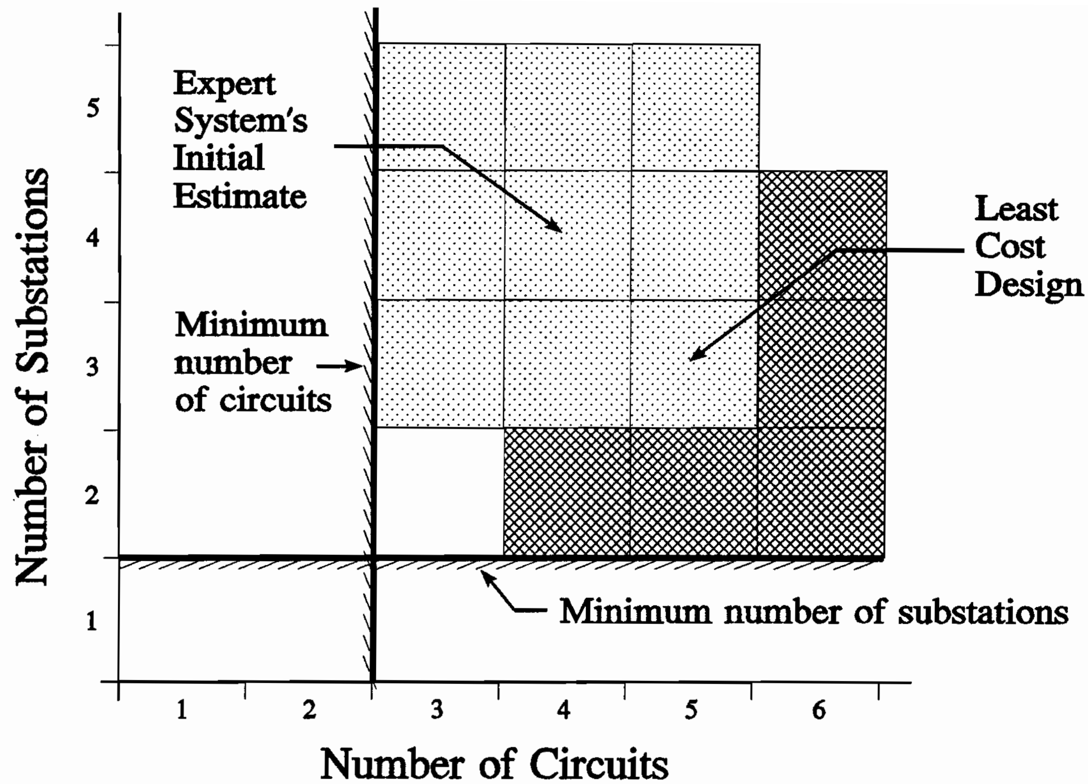


Figure 4.6: Search Example.

4.7.8 Database Module

The database rule module ensures reasonableness and completeness in the various database modules. (See section 4.6). The expert system rules guide the user when entering data so as to avoid erroneous results caused by invalid or missing data. TIDE contains many such rules, each one adapted to the specific input type. These are elaborated below.

Reasonableness

Data reasonableness includes validation for known limits (e.g. positive line resistance) as well as heuristic data trends. Data limits can be minimum and maximum values or restrictions on size or types (numeric/alpha-numeric). These rules are not hard constraints, however, but heuristics that may indicate possible errors or the unreasonableness of the data.

A simple example of this type of rule would be a prediction that as the rated voltage increases, the permissible temporary overvoltages usually decrease due to stricter control. This rule may not always apply but is a good rule of thumb and alerts the user to possible data errors. An example of required data trends is the design expertise data used for determining initial voltage estimates. (See section 4.6.5). The voltage level estimates must be nondecreasing for increasing powers and/or distances.

Rules exploiting the hierarchical structure of the database maintain consistency by permitting group data modifications. Inflationary changes in component costs is an example of group changes. Another example is that, when changing the system frequency, it is necessary to modify all component impedances.

Completeness

A minimum set of data is required when designing each transmission system. The database module is able to determine the required data for the design which may be completed through inherited or typical values. If required data is missing, the user is prompted for their values.

Another function of the database module is to manipulate data for hard disk storage and interchange between the external simulators and the expert system. Due to the class structures in the various databases, different forms of storage are used to keep not only the object values but also the necessary structural information associated with these objects.

4.7.9 Summary

Several expert system modules, Design, Simulator control, Costing, Search strategy, Menu control, and Database validation, each dedicated to a specific task in the design environment, have been described. They interact with each other and are highly integrated with the databases and the simulators.

4.8 Simulators in TIDE

4.8.1 Introduction

Power system simulators are algorithmic in nature and are used to analyze and compare the behaviour of different power systems. To use these simulators effectively for power system design requires an experienced engineer who can interpret the results and recommend appropriate system improvements. Although commercial simulator software packages are available [1], [2] they were found too cumbersome, slow and inflexible for the type of preliminary design executed by TIDE. Preliminary design requires highly integrated simulators; otherwise there tends to be a shift of focus away from design toward simulator integration [69]. Specialized simulator modules were written to obtain the desired balance between accuracy, flexibility, processing speed and integration with the rest of TIDE.

TIDE has four simulators: Voltage control, Load flow, Transient stability and Reliability. The simulators are algorithmic in nature and are best programmed in a sequential programming language. The language used for TIDE's simulators was Quick Basic [4] as it provides an excellent balance between computational, graphical and prototyping capabilities. Expertise is required to guide and control the simulator modules and this is accomplished by the Simulator control module using heuristic programming as indicated below.

An overview of the interaction among the simulators is shown in Figure 4.7. The simulators, relying on imbedded control rules, intelligently refine the skeletal AC networks suggested by the expert system. The system compensation is then modified to determine the performance of the transmission facility and ensure that it meets the design criteria. The criteria controlling the simulation tools are shown in Table 3.4 and the modelling capabilities of TIDE in Tables 3.2 and 3.3. The simulators used to analyze each of these

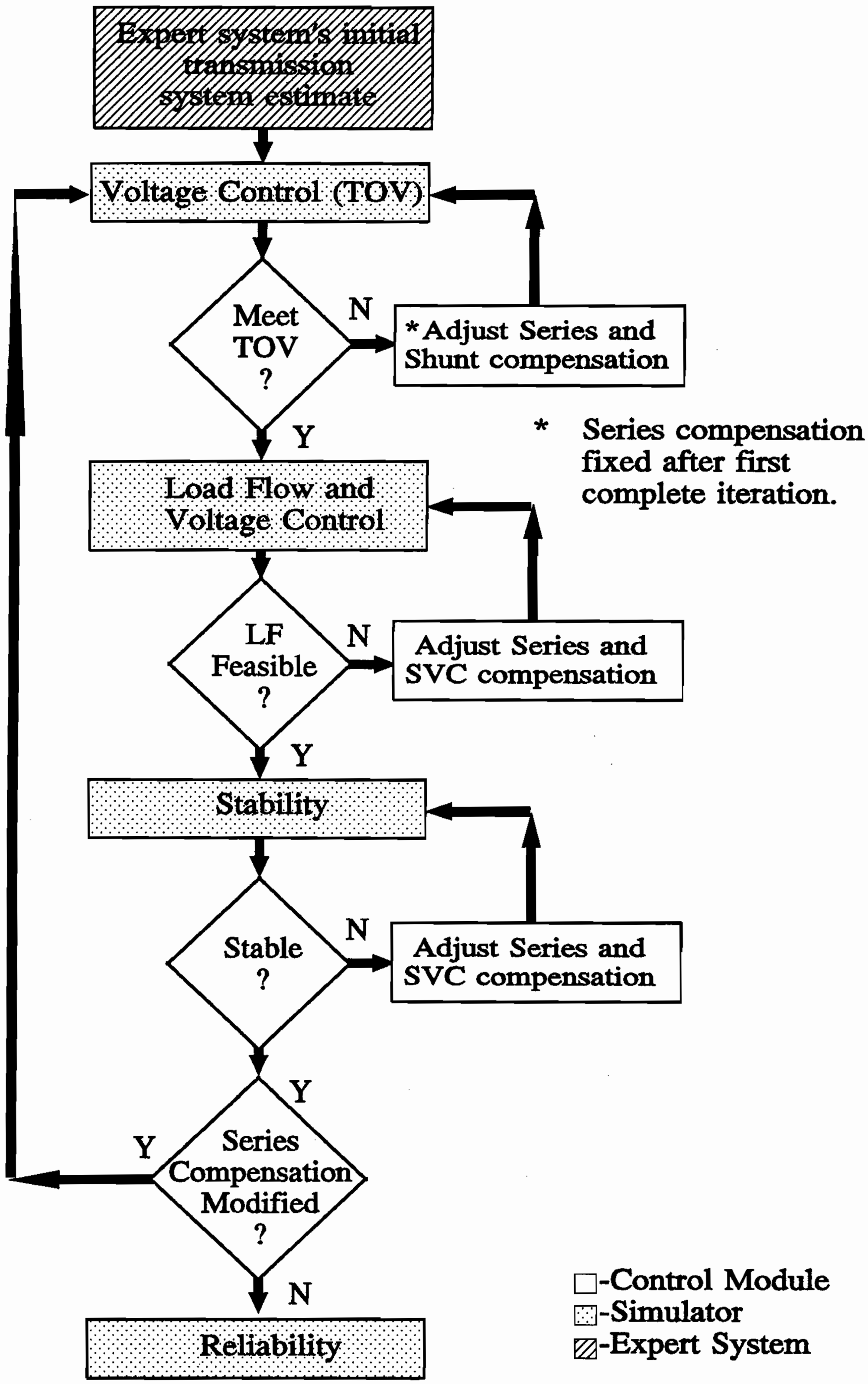


Figure 4.7: Interaction of TIDE's Simulators.

criteria and the component parameters which are varied to meet the criteria are summarized in Table 4.8. These improved transmission designs are subsequently analyzed by the expert system and costed.

Table 4.8: Simulator Tools.

Design Criteria	Simulation Tool	Varied Parameter
Temporary Overvoltage	Voltage control	Series capacitance Shunt inductance
Load flow Feasibility	Load flow	Series capacitance
Transient Stability	Voltage control Load flow Transient stability	Series capacitance SVC
Light and Heavy Load Profiles	Load flow Voltage control	SVC Generation and load injected VArs
Reliability	Voltage control Load flow Transient stability Reliability	SVC Spares (Transformers, SVC)

TIDE's simulators analyze the transmission systems in two stages, one based on the intact system and the other on the degraded systems for the reliability calculations.

The analysis of the intact system refines compensation levels to meet performance criteria. Series and shunt compensation levels are first determined to limit temporary overvoltages. The system is then designed to be stable for a fault (single-phase or three-phase) at the generator bus resulting in the loss of a line section. Reactive-power control is also simulated to ensure proper voltage profile during steady-state operation even with one or two line sections out of service depending on the stability criterion. At this stage component ratings are determined.

Analysis of the degraded networks is necessary for reliability calculations. The component ratings are now fixed and no equipment other than spares is added. The Reliability module determines contingencies to be analyzed. The transmitted power is reduced when necessary so that all contingencies meet the design criteria.

The mathematics of the component models and the voltage control, load flow and stability simulator calculations are summarized in Appendix E.

4.8.2 Voltage control

The Voltage control simulator determines the amount of reactive support necessary to limit temporary overvoltages and to maintain a flat voltage profile for various loading conditions. This analysis is performed using the Load flow and Voltage control simulators as seen in section E.3. Series capacitors and shunt reactors in each line section are used to limit the load rejection overvoltage. The amount of compensation to reach the design TOV criterion is obtained by an iterative search guided by the control module.

An example of meeting a TOV criterion through the addition of series and shunt compensation is shown in Figure 4.8A. The initial compensation estimate is about 5% for this example which results in a system TOV of 4.5 p.u. To meet the desired TOV of 1.5 p.u., both series and shunt compensation are added iteratively in discrete steps of about 5%. The TOV is met when the series compensation is 45% and the shunt compensation is 43%. Once the TOV criterion is reached, the series capacitance and SVC compensation are adjusted to meet the load flow and stability criteria in Figure 4.8B. If the series compensation is increased, then the TOV is recalculated (steps 16 and 17, Figure 4.8A), as the extra VArs supplied by the additional series capacitance may reduce the TOV shunt inductors requirements. For these TOV calculations, the series capacitance remains fixed at the value determined by the load flow/stability calculations and only the shunt reactance

Figure 4.8A Addition of Compensation to Meet the TOV Criterion

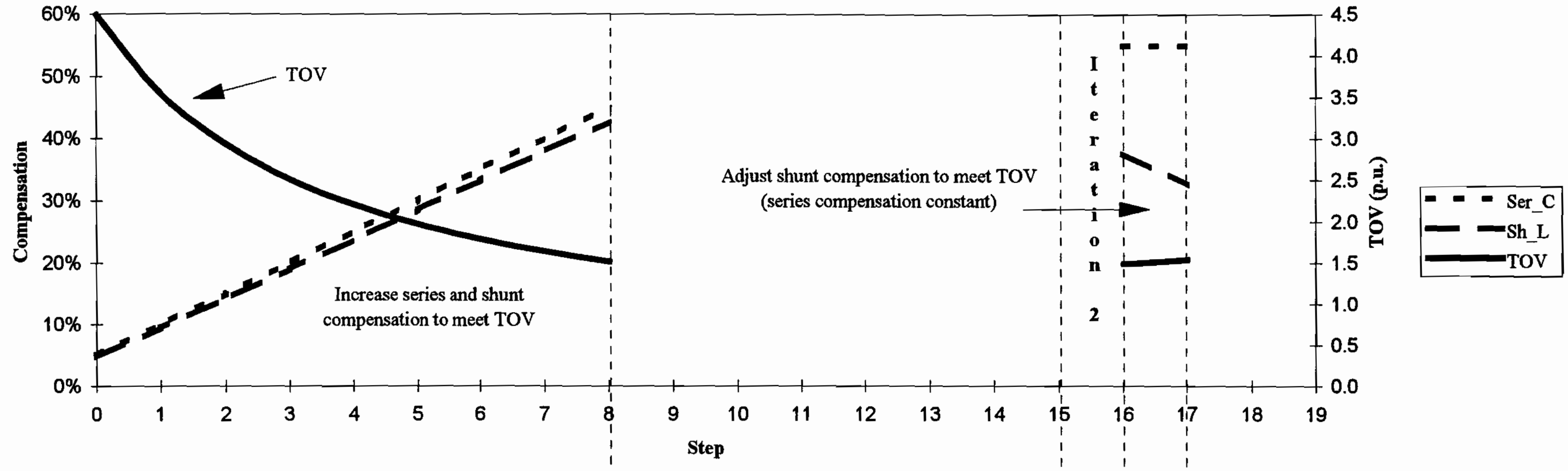
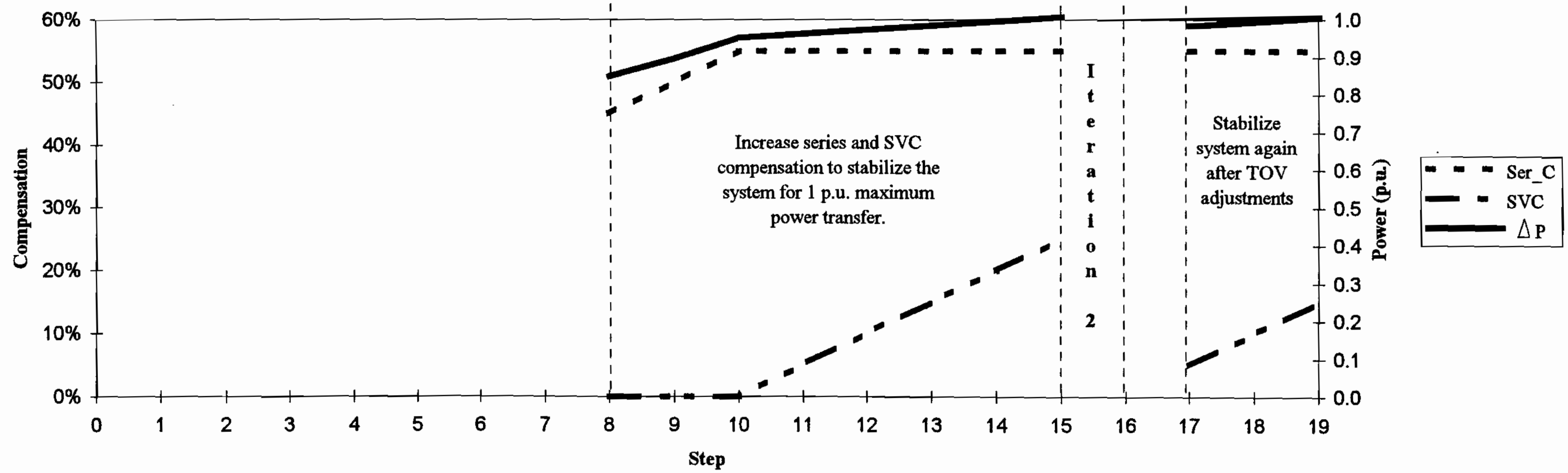


Figure 4.8B Addition of Compensation to Meet the Stability Criterion



is modified. The shunt inductance may often times be reduced which, in turn, decreases the SVC requirements when stabilizing the system. The SVC's no longer need to supply the VArs of the shunt reactors. The reader is referred to Figure 4.7 which shows the interaction between the simulator modules.

Voltage control is also required to maintain a flat voltage profile under heavy and light loading conditions [34],[52]. The amount of injected reactive power at each bus necessary to maintain a flat voltage profile is transformed into an SVC rating in terms of VAr injections. Ratings for generation and load VAr injections are also determined from the voltage simulation. The methodology to determine the reactive power necessary to maintain a flat voltage profile is shown in section E.3.

This module was validated using CYMFLOW [1] for a sampling of network configurations. The TOV test networks consisted of a single source connected to a set of busses with zero load. The Voltage control was validated using PV buses at all intermediate substations and at the load. The results were accurate to within the expected accuracy of TIDE's simulator and the tolerance of CYMFLOW.

4.8.3 Load Flow

Load flow determines the steady-state performance of the power system by determining voltage profiles, power flows on the lines and line losses [45]. The Load flow simulator, guided by the control module, determines the amount of compensation required to make a design load flow feasible. The before-fault load flow must be feasible under heavy loading conditions with loss of n parallel line sections as well as under light loading conditions. The after-fault load flow is made feasible with m parallel line sections out after the fault. Series compensation is added until the network is feasible. If the maximum allowable series compensation level is reached, SVC is added instead.

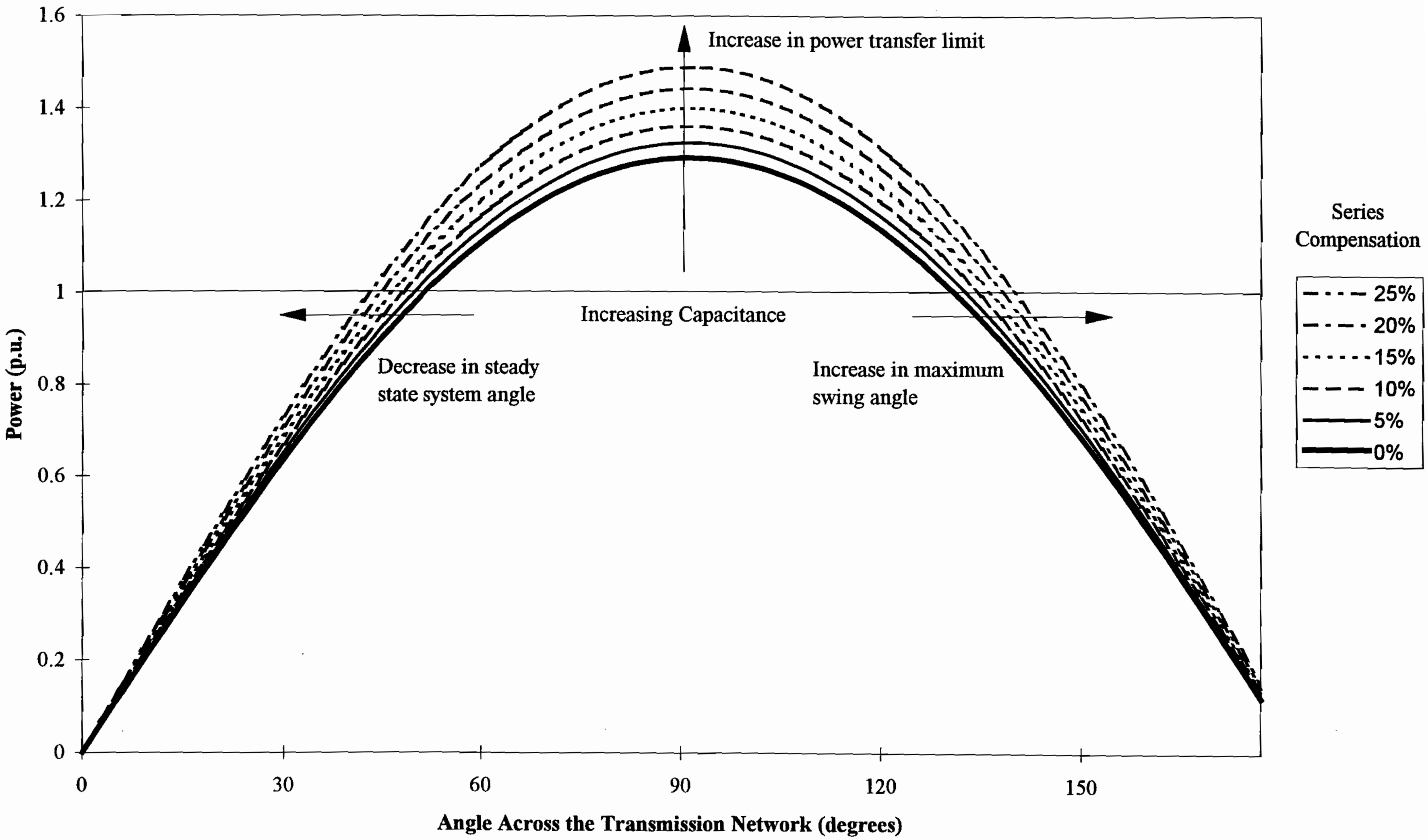
The Load flow simulator was written in QuickBasic and validated using CYMFLOW as described in section 4.8.2. In TIDE, even in the case of multiple lines and substations, the point-to-point network can always be reduced to an equivalent π. The load can therefore be solved analytically and is very fast. Furthermore infeasible load flows can be readily be identified. The equations used in the network reduction and the load flow calculations are shown in Appendix E.

4.8.4 Transient Stability

The Transient stability simulator uses the equal-area criterion [97] to determine if the networks are stable. This is possible as there is only one generator connected to the load which is modeled as an infinite bus. As these designs are being considered for preliminary analysis only, indirect numerical simulation techniques were not considered necessary. The lack of damping and generator control systems in the stability network models tends to make the designs more conservative [31]. In any case, analysis using a fully detailed transient stability model is unwieldy to use for preliminary planning and would consume too much time within an environment such as TIDE [25]. The mathematical formulation of the equal-area stability method is discussed in section E.3.

The before-fault conditions of the stability simulator are a user-specified n line sections out while maintaining a flat voltage profile under full load. A single-phase or three-phase fault is then applied to the generator bus for t_c cycles simulating a worst-case scenario. Single-phase faults are approximated by dividing the three-phase fault duration by six. This approximation has been verified by experience and by using more precise simulation packages. The fault is followed by a loss of a user-specified m line sections to simulate the protection system removing line sections in an attempt to clear the fault. If the system is unstable, series capacitance and SVC's are added until the system is stabilized or the maximum allowed compensation is reached. The effect of adding series compensation to a power system is shown in Figure 4.9 where it can be seen that there is an increase in the maximum power transfer limit, the maximum swing angle as well as a decrease in the steady-state system angle.

Figure 4.9 Increased Power Transfer Through the Addition of Series Capacitance.



4.8.5 Reliability

The basic methodology of calculating reliability indices involves selecting the most relevant system states and then simulating the corresponding system response (including remedial action) from which are calculated the system reliability indices. The most usual state selection methods are Monte Carlo simulation and state enumeration [73]. The system response is calculated based on load flow, optimal power flow and transient stability programs. These simulations identify either static overloading and over/under voltages, or dynamic problems such as machine speed instability or voltage collapse [61].

State enumeration techniques use Markov models to represent the random transition between system states and calculate reliability indices. Monte Carlo simulation methods estimate reliability indices by randomly simulating system states. Monte Carlo techniques can be more easily used with large and detailed system models [7] but require the simulation of an extensive number of cases. In the scope of preliminary planning, the data for detailed simulation is not readily available, the number of states is not very large, a high degree of accuracy is not required and a large amount of computing time is not justified. Thus, state enumeration techniques are better suited to preliminary planning and are discussed in more detail below.

The reliability calculations of TIDE are applied only to the transmission facilities. As generation is common to all transmission systems being studied, it was not felt necessary to consider it in the study of reliability. Both system adequacy and security are calculated in the reliability module. The reliability calculations require investigating the system's behaviour under a variety of contingencies.

A contingency is an event which may result in system instability or in a degraded power system due to the loss of one or more components. The calculation of the reliability indices involves examining loss-of-load impact of each contingency starting with the most likely and terminating when the remaining contingencies become so improbable that they can be ignored or lumped together [24].

All outages are assumed to be independent; in other words, no common-mode outages are considered, although multiple outages are indeed examined [17]. Statistical failure data of typical equipment is readily available in a number of databases [20], [23]. Steady-state dependent outages such as reducing power to avoid overloading the remaining circuits after the loss of a line section are also considered. System outages comprising common-mode and station oriented outages are not considered as this level of detail is not necessary for preliminary planning.

In TIDE, the data required for the reliability calculations are supplied from three database modules: Design criteria, Transmission systems and Equipment databases. The Design criteria database contains the overall performance objects including: the annual peak load-duration curve, the target reliability indices and the number of contingency levels and states to be evaluated. The topology of the system to be analyzed is contained in the Transmission systems database. The Equipment database provides individual component characteristics such as: impedances, failure and repair rates, component ratings, failure modes and the available spares.

The following sections discuss the Reliability module in more detail. The first section examines the reliability models of the various system components. The remaining five sections enumerate the steps in determining system reliability and their interaction is outlined in Figure 4.10.

4.8.5.1 Reliability Component Modelling

The power system components are represented by a two-state model, the intact state and the failed state. Component failure (λ)and repair rates (μ) are used to calculate the probability of being in either state according to,

$$AV = \frac{\mu}{(\mu + \lambda)} \qquad (4.1)$$

and

$$U = 1 - AV = \frac{\lambda}{\lambda + \mu} \qquad (4.2)$$

where AV is the availability of the component and U is its unavailability, that is, the probability of being in a failed state. The individual failure probabilities are then combined, assuming failures are independent, to determine the overall system reliability as shown in 4.8.5.2. The following paragraphs and Table 4.9 summarize the Reliability model of each component.

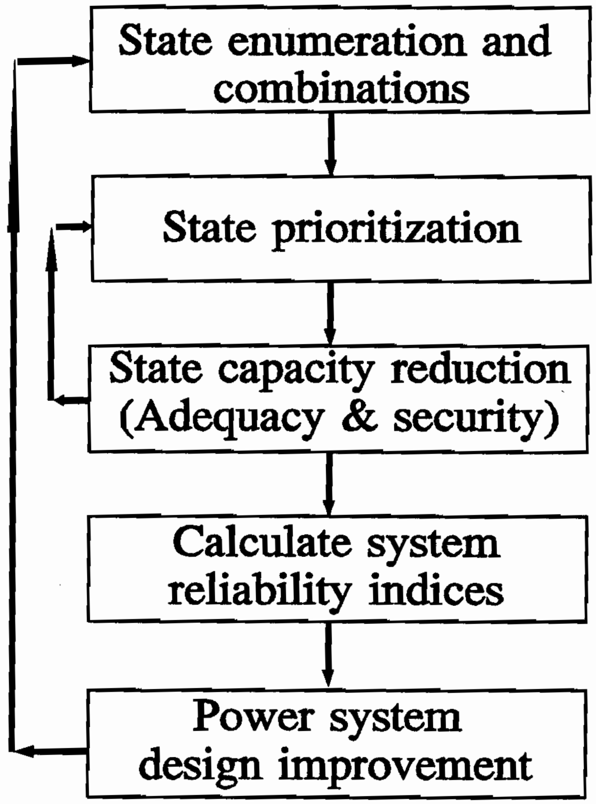


Figure 4.10: Expert System Controlled Reliability Calculations

Transformer:

Sending-end and receiving-end transformers are represented by two-state models. The failure and repair rates are specified for each type of transformer. Spare transformers are assumed to be on-line. Transformers are considered as independent devices in parallel and are limited by a thermal MVA rating.

Transmission lines:

Transmission line sections between substations are represented by two-state models. These can fail individually or in series and parallel combinations, of which some examples are shown in Figure 4.11. Each transmission line section is modelled as having the same impact as any other line section. The failure and repair rates are divided into two parts, one for terminal equipment and the second proportional to the line length. The

Table 4.9: Reliability Modelling of Component Data.

COMPONENT	STATE MODEL	TOPOLOGICAL CONSTRAINTS	SPARES
Transformer	2-state	MVA rating	On-line components
Line section	2 state	Ampacity	
Series compensation	2 state	Ampacity	On-line overrating
Shunt compensation	2 state	MVAr rating	
Static var compensation	2 state with discrete components	MVAr rating	On-line overrating
DC Terminals	2 state	MW rating	
Generation	Not considered	Transmitted power	
Load	Annual Load-Duration Curve	Peak load	
Substation	2 state		
Corridor	Not required for comparison		

transmission lines are limited by an ampacity rating. The probability of being in a combined state such as those shown in Figure 4.11 is given in section 4.8.5.2.

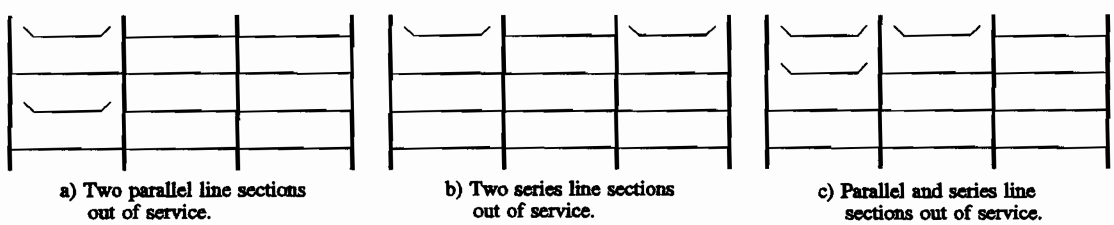


Figure 4.11: Transmission Line Failures.

Compensation:

The loss of any series capacitor or shunt reactor is modelled as having the same impact for all line sections. Series compensation is limited by its steady-state current rating and the shunt reactor by its MVAr rating.

Each static VAr compensator can be modelled as a single two-state model or as many two-state models for degraded operation. The effect of the loss of any SVC is assumed to be independent of its location. The SVC is limited by its MVAr rating.

DC Terminals:

For DC reliability calculations each pole of the DC terminal is modelled independently as individual two-state models. Single pole derated states, such as loss of a single filter, are not considered as this level of accuracy is not required for preliminary transmission analysis. The reliability failure rates and repair durations include those of the valves, the AC filter systems as well as the remaining components of the DC terminals.

Generation and Load:

The reliability of the generation is not considered in TIDE as it is common to all transmission systems. The load is modelled using an annual load-duration curve based on average consumption which is used to weigh the reliability calculations for each state. A sample load-duration curve is shown in Figure 4.12.

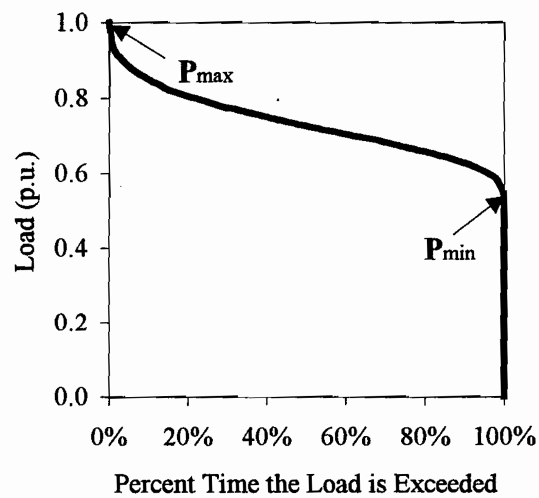


Figure 4.12 Load-Duration Curve.

Substation or Corridor

Substations are modelled as two state models. The loss of a corridor is not considered as it is assumed to be similar for all designs.

4.8.5.2 State Enumeration and Combinations

The state of the entire system is defined by the states of the individual components. Each system state is referenced by an identification number described by the following information:

- the probability of this system state occurring,
- the power reduction necessary to meet adequacy and security,
- a list of the failed components.

A failure tree is used to represent graphically the various system states. The lines joining these states indicate the possible failure and repair paths. An example of such a failure tree for an AC system is shown in Figure 4.13. This tree is divided into levels of contingencies corresponding to the number of failed components. State 1 represents the intact system or the zero-level contingency. The first level contingencies (states 2-4) consider the failure of any single component. In Figure 4.13, state 2 denotes the failure of a sending transformer (T), state 3 is the failure of a line single section (L) and so forth. The data below the system state numbers represent: the probability of the state, the loss-of-load needed to satisfy normal steady-state operation (ie. all limits satisfied) and the failed components. Figure 4.13 also shows the load-duration curve assumed and a single-line-diagram of the network. The second level of contingencies (states 5-10) represents any two failed components consisting of either similar components or combinations of different components. The failure tree shown in Figure 4.13 is truncated at the third contingency level. TIDE is capable of truncating the failure tree at a level meeting a minimum desired error in the reliability calculation.

When determining the probability of a given state, each type of component is considered separately to simplify the computational procedure. For each type of component, failure states are identified. Inherent in state identification is state reduction by combining similar states. This becomes particularly important as the number of states increases exponentially with the number of components considered. Identical component

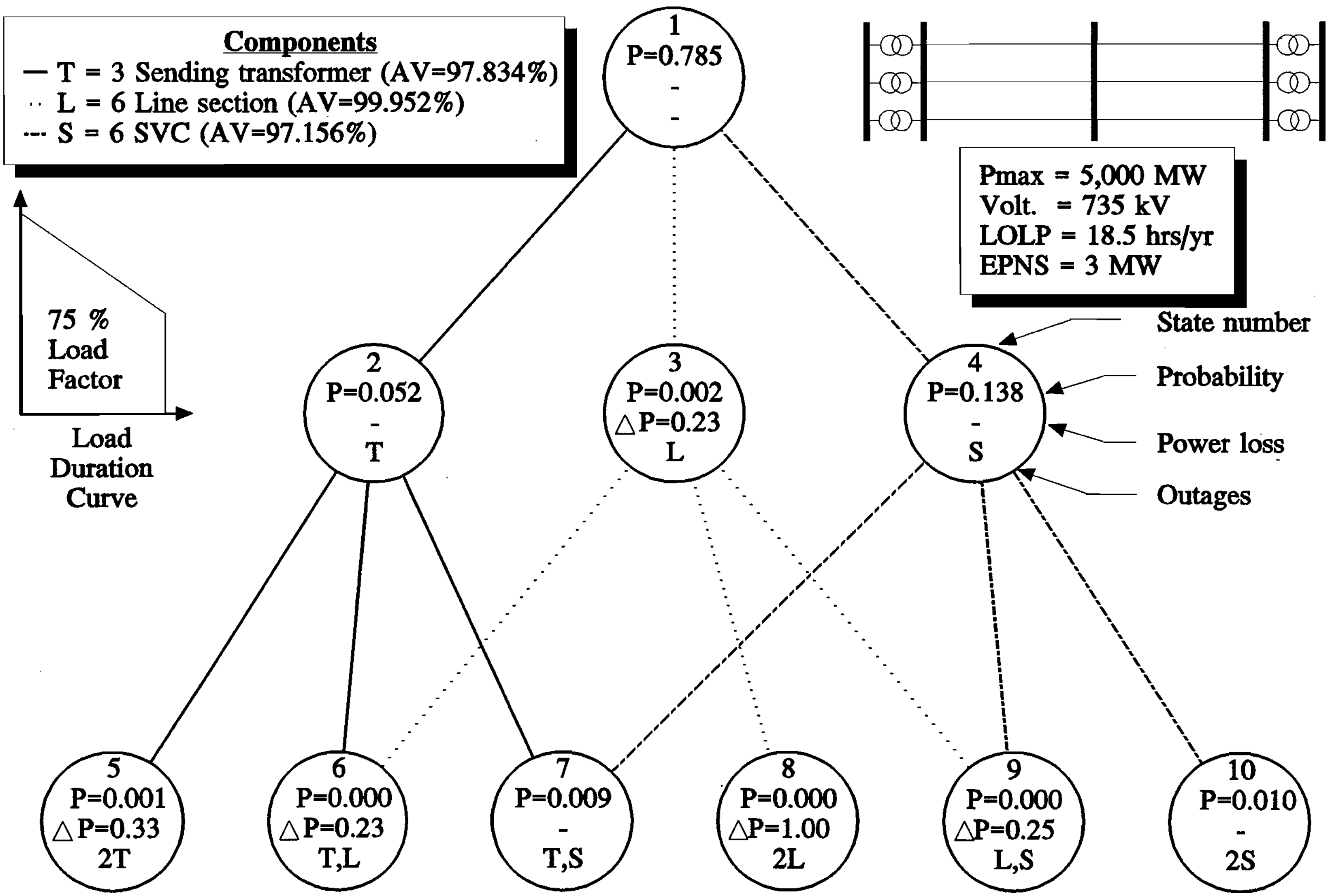


Figure 4.13: Reliability Failure Tree (Space-state diagram).

outages are thus combined into a single equivalent state if their failures are equally likely and have similar system effects on the system security and adequacy. The power loss due to an equivalent outage-state is assumed to be representative of all other similar states.

The probabilities of each equivalent state are determined based on the longterm availability (AV_i) of a single component i given by equation (4.1) and by the number of identical states. For example, the probability of being in an equivalent component state defined by component type i with r failed identical parallel components out of n_i total components is,

$$P_{r,i} = {}^{n_i}C_r \, AV_i^{n_i - r} \, (1 - AV_i)^r \tag{4.3}$$

where ${}^{n}C_r$ is the number of combinations of r items from n items. When components, such as line sections, may have both series and parallel elements, the total number of combinations may be further subdivided.

Another example of equivalent states is the grouping of the possible failures of all the AC line sections as shown in Figure 4.14. To group these states in terms of their impact on security it is assumed that the effect of a fault on a given line section and its subsequent removal is equivalent to that of a fault on the section closest to the generator. Figure 4.14 shows the effect of combining similar states on the failure tree for a small AC system with two parallel lines and one intermediate substation. In this example, 16 states are reduced into 6 equivalent states. Each of the state groupings are determined as follows:

States for the individual line outages L1 through L4 are combined into one state (1L) which has a probability of,

$$P_{1L} = {}^{4}C_1 \, AV^3 \, (1 - AV) = 4 \, AV^3 \, (1 - AV) \tag{4.4}$$

where AV is the availability of a line section.

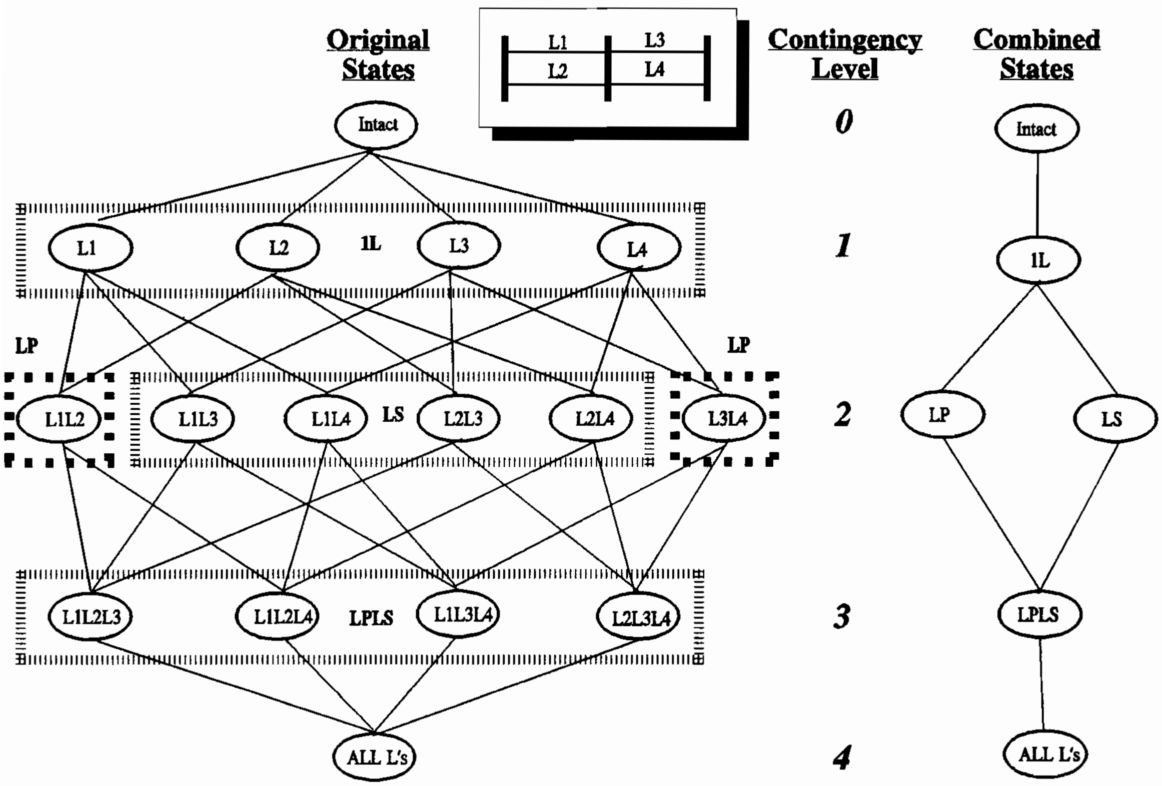


Figure 4.14: Topological state combination example.

The combinations of two line sections out are lumped into two states of lines in parallel (LP) and series (LS). The total number of failure states of contingency level 2 is given by ${}^4C_2 = 6$. Of these 6 states, 2 correspond to the loss of 2 parallel lines (LP), while the remaining 4 correspond to the loss of 2 line sections in series (LS). The corresponding probabilities are,

$$P_{LP} = 2\ AV^2\ (1 - AV\ )^2$$
$$P_{LS} = 4\ AV^2\ (1 - AV\ )^2 \quad \textbf{(4.5)}$$

The third contingency level can be combined into one state (LPLS) with two line sections in parallel and one in series. The probability of this equivalent state is,

$$P_{LPLS} = 4\ AV\ (1 - AV\ )^3 \tag{4.6}$$

Using the previously described component state combination, the probabilities of the actual combined system states can be calculated. The system states include the combined states of a number of different components such as transformers, lines, SVC's, etc. The combined state probabilities are obtained by multiplying the individual state probabilities, which is possible as the components failure and repair rates are assumed to be independent.

An example of combined system states can be seen by returning to Figure 4.13. This network has three sending transformers (T), six line sections (L) and six SVC's (S). The following simplifications are made to the reliability network so as not to complicate this example:

- The receiving-end transformers are ignored.
- Series line section outages are lumped together with the parallel line outages. This would mean for the example in Figure 4.14 that states LP and LS would be combined into one equivalent state.

These simplifications will increase the system reliability index as line sections in series are less severe than line sections in parallel.

Referring to Figure 4.13, the probability of being in state 1, in which no components have failed, is given by:

$$\begin{aligned} P_1 &= P_{0,T}\ P_{0,L}\ P_{0,S} \\ &= AV_T^3\ AV_L^6\ AV_S^6 \\ &= (.97834)^3\ (.99952)^6\ (.97156)^6 \\ &= .7853 \end{aligned} \tag{4.7}$$

where $P_{0,T}$, $P_{0,L}$ and $P_{0,S}$ are the probabilities of having no transformers, line sections and SVC's respectively out of service. AV_T, AV_L and AV_S are the corresponding availabilities.

The probability of being in state 7 of Figure 4.13, where one transformer and one line section have failed, is,

$$\begin{aligned} P_7 &= P_{1,T}\, P_{0,L}\, P_{1,S} \\ &= \left(3AV_T^2\,(1-AV_T)\right) AV_L^6 \left(6AV_S^5\,(1-AV_S)\right) \\ &= \left(3(.97834)^2\,(.02166)\right)(.99952)^6\left(6(.97156)^5\,(.02844)\right) \\ &= .0092 \end{aligned} \tag{4.8}$$

where $P_{1,T}$ and $P_{1,S}$ are the probabilities of having a single transformer and SVC fail.

In order to reduce the computation time, the failure tree may be truncated and certain states ignored. The contingency level at which the failure tree is truncated is user specified. The probability of the remaining states is given by ($1-\sum_{j=1}^{M} P_j$) when M states have been considered. The complete system is assumed to be lost for the states not considered, and their probability is added to the system reliability index.

DC system state diagrams can also be reduced using similar arguments. DC lines, for reliability considerations, are considered to be directly connected to a terminal pole. The loss of a pole can be caused by the failure of the transmission line pole or by either terminal at the ends of the line.

4.8.5.3 Transmission Capacity Reduction

For a state to be considered acceptable, it must meet the system steady-state and transient security criteria. The criteria considered under steady-state are component overloading, voltage profile and load flow feasibility. The system may also be required to satisfy these criteria for any subsequent single-level contingency as well. For transient operation, the system must be stable for a single-phase or three-phase fault while maintaining an acceptable voltage profile after the fault is cleared. If these criteria are not respected, it may be necessary to reduce the maximum possible power transmitted (transmission capacity) for that particular state [41]. This capacity reduction may or may not result in a loss of load depending on the actual power demand at that time as defined by the load-duration curve. The same models as described earlier are used to calculate the capacity reduction. As an example, in Figure 4.13 the loss of two transformers (state 5) results in a transmission capacity reduction of 33% of the total transmitted power.

4.8.5.4 Reliability Indices

The reliability indices provide probabilistic measures of the system's ability to meet the adequacy and security criteria. Loss-of-load probability (LOLP) and expected power not supplied (EPNS) are the reliability measures used in TIDE [75]. These reliability indices are calculated from the system state probabilities and the corresponding capacity reductions. The LOLP reliability index is the sum of all the state probabilities (P_i) that result in a loss of load while EPNS is the sum of the products of the state probabilities and the corresponding loss-of-load, ΔP_i.

As a power system does not usually operate with a 100% load factor, the loss of transmission capacity due to transmission outages does not necessarily result in a loss of load. Clearly, if the outage occurs when the load is low, a loss of capacity may have no impact at all. To account for load variations, the reliability indices are weighted by the inverted load-duration curve (ILDC). The $ILDC_i$ is the probability that the load is greater than the maximum transmission capacity for state i [24]. Thus,

$$LOLP = \sum_{i=1}^{n} P_i * ILDC_i \tag{4.9}$$

$$EPNS = \sum_{i=1}^{n} \Delta P_i * P_i * ILDC_i \tag{4.10}$$

4.8.5.5 State Prioritization and Pruning the Search Space

In the reliability calculations, the most computationally intensive process in designing a preliminary transmission system is determining the transmission capacity reduction for each state. In order to limit the computational burden, the states are prioritized according to their probability and only a limited number are considered.

A first pass in reducing the number of states is to specify the number of contingency levels to be considered which, in TIDE, is typically four to five. Knowing the probability and power reduction of a given state enables the importance of subsequent contingencies to be predicted. The deeper the failure tree is descended, the lower the probability of the corresponding state and the higher the transmission capacity reduction will be. States that are considered improbable eliminate the need for further analysis of subsequent states deeper into the tree [13].

4.8.5.6 Design Improvement

The Design improvement module of TIDE uses the reliability calculations to identify areas of weakness of a transmission system and suggests possible design improvements through the addition of spare components or overrating of equipment. This section discusses a methodology to determine the optimal number of available spare components to meet a minimum reliability criterion and to minimize overall system costs.

The first step in design improvement is to determine the areas of *system weakness*. These are identified by breaking down the LOLP and EPNS reliability indices and apportioning them to the components causing the greatest unreliability of that state. Simple heuristics, based on previous contingency levels, are used to identify which unavailable component is most likely to cause the power reduction. In addition to the LOLP and EPNS indices, the number of outages as well as the total outage capacity caused by a component are calculated by TIDE in identifying system weaknesses. The total outage capacity is the sum of all the capacity reductions associated with that component and differs from the reliability indices which are weighted by the state probability. These indices provide the system planner with an indication of the system weakness caused by various components. An example of system weakness would be a system having transformers with a very high failure rate but only having a single spare transformer at each substation. The transformers in such a system could then dominate the system's unreliability and be the major cause of power outages.

Once the main causes of unreliability have been identified, system reliability can be improved by the addition of spare components or by overrating equipment. The term spares can refer to the availability of additional components or to replacement parts to repair damaged components.

The availability of spare parts is not treated explicitly in this section, however spare parts can be analyzed in TIDE by creating new components with adjusted repair times and costs. Additional costs incurred due to the availability of spare parts may include storage fees and carrying charges. These costs can then be factored into the component capital cost and the repair time decreased accordingly [43]. As TIDE considers all combinations of components, systems with and without additional spares parts can be compared. Examples of the use of spares by TIDE to improve reliability are described in section 5.7.

For DC systems, TIDE only analyzes spare parts as described above. DC lines and terminals are considered to be part of the system topology and therefore do not have spares. Variations of ratings and number of lines, however, can be analyzed by the DC design expert system.

In TIDE, spare components are taken to be those which do not change the system topology or the intact system response. For AC systems, the spare components considered are *sending and receiving transformers* and *SVC's*. Components such as additional circuits or substations are not considered in this analysis as spare modules but instead as design parameters. Series capacitors and shunt inductors, being attached to individual line sections, are also not considered as spares. Series capacitors are, however, designed to have on-line spare capacity to ensure that they will remain in service transmitting the full load despite one line being out of service.

When the Design improvement module is not being used, spare components are assigned to meet the N-1 criterion or more specifically, SVC's are overrated by 30% and an extra transformer is added to either end of the transmission system. When using the Design improvement module, the N-1 criterion for transformers and SVC's is relaxed and spares are allocated based either on economics or on meeting, if possible, a minimum level of reliability according to LOLP or EPNS. The N-1 criterion for the rating of series compensation and loss of a line after a fault remain unchanged. When based on economics, the number of spares then becomes a function of the overall system reliability, the cost of unreliability and the number and size of each component [62]. Cost savings may be realized by adjusting the number of spares to reflect high component reliability levels or low system unreliability costs resulting in a more equitable system comparison.

The overall system cost is adjusted to reflect the number of additional spare components. Intermediate designs may be saved as each spare element is added. This enables the system planner to determine the sensitivity of the system reliability to that component as well as to analyze the tradeoff between the cost of unreliability and the component capital cost. As more spares are added, their effect on the system reliability will saturate resulting in marginal improvements in reliability as the dominant cause of unreliability will shift to other components. If the system reliability cannot be improved sufficiently to meet the desired reliability criterion, then alternative systems suggested by TIDE should be considered. Examples of this design process are found in Chapter 5.

4.8.5.7 Reliability Summary

Calculating the reliability of the transmission facility provides an additional measure other than deterministic criteria to enable the comparison of transmission systems. System reliability is determined through state enumeration controlled by expert systems to limit the number of states and to combine them into equivalent states. The reliability criteria, LOLP and EPNS, are based on the probability of each state and in the corresponding power transmission capacity reduction to ensure secure operation.

Reliability calculations can be used not only to calculate system reliability but also to identify system weaknesses and improve system reliability through the addition of spare components.

4.9 User Interface of TIDE

A user-friendly menu-based interface has been developed for TIDE. Dynamically updated menus and context-sensitive help assist the system planner to enter the required data and to examine the design results in a variety of forms (graphs and tables). Explanations are also provided during the design process to facilitate comprehension of the design methodology. An overview of the principal menus and options is contained in Appendix A.

4.10 Summary

TIDE is an intelligent environment for the preliminary design of point-to-point transmission facilities. Transmission design is a creative, multifaceted process which relies on a design engineer's experience and intuition as well as a variety of power simulation tools. A similar approach is used in TIDE where a hybrid of different techniques work harmoniously together to represent and process the design knowledge necessary to perform the preliminary design of transmission systems. These various techniques are divided into the following categories, object databases, expert systems and simulators. Each category exploits the strengths of each technique which integrates knowledge processing with classical calculation techniques resulting in a structured and efficient design tool.

Both the expert systems and simulators reason on the hierarchical object-databases. There are five object-databases used to represent *equipment*, *design criteria* and *expertise*, the *results* as well as the *housekeeping*. The database permits the knowledge and inherited methods to be structured in a way to be reused by various expert systems and simulators.

Expert systems represent the design heuristics which were modelled based on transmission design engineer's rules of thumb as well as recognized design methods. There are six expert system modules in TIDE. The *design* expert system forms skeletal structures which are costed by the *costing* module after being analyzed and refined, a task which is overseen by the *simulator control* module. Subsequent designs are suggested by the *search strategies* module which are, in turn, simulated and costed. The user is directed between TIDE's various screens by the *menu control* expert system module and warned of possible inconsistencies or database problems by the *database* expert system module.

The algorithmic portion of TIDE is programmed in a sequential language and are divided into four simulators, each focusing on a different aspect of transmission design analysis. The simulators are *Voltage control*, *Loadflow*, *Transient stability* and *Reliability*. The simulators refine the initial designs, ensure the design criteria are met as well as provide a performance summary of the intact and degraded system of the various designs.

CHAPTER 5

RESULTS

5.1 Introduction

A wide range of transmission design options can be rapidly examined using TIDE from the points of view of cost, reliability and transmission performance (overvoltages, voltage profile and stability). Various transmission systems are studied in this chapter illustrating the different aspects and capabilities of TIDE. Basic results showing the trade-off between cost and reliability are demonstrated using the Hydro-Québec system. For further demonstration purposes, and validation of TIDE, three sample case studies of existing North-American transmission systems are considered. Finally, more generalized transmission results are presented covering a wide range of powers and distances focusing on voltage and cost and their sensitivity to various design criteria.

The sample case studies consist of two AC and two DC power systems ranging in delivered power from 1,800 to 13,000 MW and distances from 600 to 1,000 km. TIDE's results do not exactly match the existing power utilities transmission designs due to changes in component costs and the consideration of additional detailed design criteria such as political or environmental considerations or regional voltage standardization. Nevertheless, the results obtained from the design examples are sufficiently comparable to the actual designs to demonstrate the capabilities, reasonableness and usage of TIDE's design environment.

5.2 Test Data

A common database is used for all the sample case studies included in this chapter unless otherwise specified. The database is summarized in Appendix B and contains design criteria and equipment data for 8 voltage levels, namely, 1200, 735, 500 and 315 kV AC and 800, 600, 450 and 250 kV DC. The equipment characteristics are based on data obtained from Hydro-Québec's planning department [19] and the reliability data from the Canadian Electrical Association's Equipment Reliability Information System (ERIS) [20] and Conférence Internationale des Grands Réseaux Électriques (CIGRÉ) [23]. When data was not readily available, extrapolations were made with the help of a system planning expert [84]. Of course, through TIDE, the user can easily modify this database by addition, subtraction or modification of equipment and design criteria.

The AC design criteria in this test database were chosen as follows: (1) maximum permissible temporary overvoltage following load rejection ranging from 1.3 to 1.6 pu (see Appendix B), (2) load flow feasibility and steady-state flat voltage profile with 1 line section out, (3) stability for a three-phase 6-cycle fault followed by the loss of one line section, (4) a minimum of two AC lines and a maximum of 60% series capacitance and 50% static VAr compensation (SVC), (5) overrating of SVC's by 33% (6) one spare transformer at both sending and receiving ends, and (7) overrating of series capacitors to handle full load with one line out of service.

The selected DC design criteria are: (1) a maximum voltage drop across the lines of 10%, and (2) minimum of one DC bipole (single-pole operation permitted). It is assumed that the loss of 1 pole of any bipolar DC line will not affect severely the rest of the power transmission system. A maximum allowable percentage of the total power lost due to the loss of a single pole may also be specified.

Other overall system specifications applicable to both AC and DC design are: (1) operation of all components within their ratings, (2) transmission losses and expected load outages are costed at 2,000 $/kW, and (3) the load has a 75% utilization factor. The costs used for these studies are in 1991 dollars. (See Appendix B).

5.3 Design Example

The first system to be studied is the first stage of Hydro-Québec's 735 kV transmission system. (See Figure 5.1). 5000 MW of hydroelectric power is supplied by generating stations near Manicouagan to the Boucherville/Duvernay substations which in turn feed Montreal through a 315 kV transmission system. The transmission system, built in 1965, had three 735 kV lines spanning a distance of approximately 600 km with one intermediate substation, no series compensation, 30% shunt inductance compensation and 1000 MVA of dynamic compensation (synchronous condensors). The system was designed to be stable for a 6-cycle single-phase fault, with three-phase clearing and no reclosure.

The three transmission lines of the Manicouagan system were split up into two transmission corridors for improved reliability and future expansion. The intermediate and load substations of the two corridors are separated by about 30 km and are joined by short transmission lines. The generation consists of seven generating units supplying power to two generating substations by 315 kV radial feeders. The 735 kV generating substations are separated by a distance of about 60 km. Since the commissioning of the transmission system, the network has been expanded with the addition of transmission lines, series compensation, generation and loads. The original system design has been retained for the purposes of this discussion to avoid the additional complications of the present day system.

Preliminary transmission design does not require large, detailed databases to give an indication of the best type of transmission system. Based on the actual system, one can

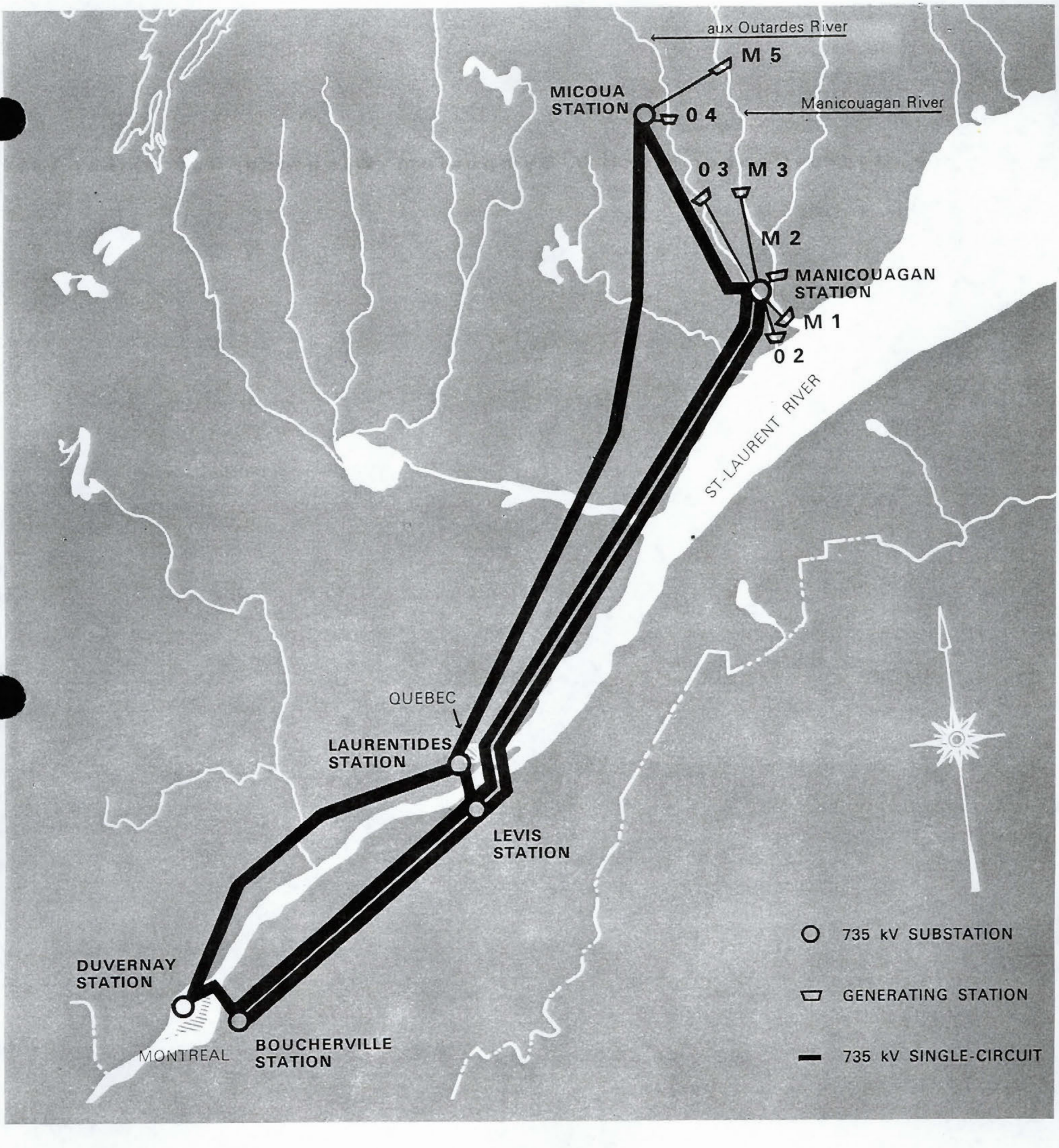


Figure 5.1: Geographical Diagram of the Manicouagan System [71].

reconstruct the initial design in a more simplified form and, at the same time, indicate the assumptions used by TIDE in this reconstruction. These assumptions are now discussed to indicate how the designs suggested by TIDE are related to a real-world system. For example, the temporary overvoltage was relaxed to 1.6 p.u. for all voltages except 1200 kV AC from the values indicated in Appendix B to simulate the switching out of shunt reactors at full load necessary to provide voltage support in the system.

To model such a system in TIDE it is necessary to make certain assumptions:

1) TIDE presently considers only one transmission corridor, therefore the six existing substations are replaced by three equivalent substations. As the "loss of a corridor" contingency is not considered in TIDE, this simplification will not affect the comparison of the resulting designs.

2) TIDE assumes substations to be equidistant, however the actual intermediate substation is located at Lévis, near the major load centre of Québec City, which is 379 km from Manicouagan. This results in a marginally different distribution of the compensation at the substations which may slightly affect the amount of compensation required to maintain a flat voltage profile.

3) TIDE supplies the complete 5,000 MW over the 600 km corridor without considering intermediate system loads. The actual system is connected to some small loads through a 315 kV subsystem at each of the intermediate substations.

The detailed stability analysis performed by Hydro-Québec determined that the 315 kV connections at the generating and intermediate substations resulted in a significantly more stable system and were indeed necessary to maintain stability for a single-phase fault [71]. In TIDE's design process, the full 5,000 MW of power are being transmitted over the entire 600 km and there is no stabilizing influence of the 315 kV subsystems.

Consequently, the designs suggested by TIDE require more compensation to achieve the same level of stability.

In the preliminary design of the Manicouagan-Boucherville/Duvernay transmission system, Hydro-Québec's system planners considered four voltage levels, namely, 315, 500/525, 650 and 735 kV AC and up to 60% series compensation. It is important to recognize the technical context of this design. At that time, 735 kV transmission did not exist and 500 kV was the highest transmission voltage being considered [21]. Thus, the 1,200 kV AC and 800 kV DC voltage levels would not have been viable options. Transmission systems were compared based on economical analysis including capital costs and transmission losses. Preliminary stability calculations were based on steady-state angles across the system. The objective was to compare designs with similar dynamic performance to ensure an equitable economic comparison. The system angle was adjusted using series compensation.

Using the above-mentioned data and design criteria, TIDE analyzed several hundred alternatives using all eight AC and DC voltage levels in a *question of minutes*. This is in sharp contrast with the several weeks required in the original study. TIDE determined the least-capital-cost design to be a 735 kV, three-line AC system with a single intermediate substation which is the same basic topology as the original Manicouagan-Montreal transmission system. A summary of 13 designs suggested by TIDE is shown in Table 5.1. The designs are ranked according to cost. For the sake of completeness, Table 5.1 also displays three additional designs (A to C) not normally suggested by TIDE because of their excessive cost. Designs A and B were considered by the original designers.

Note that in arriving at the final transmission line designs, several types of conductors were considered by TIDE and the least cost conductor was retained.

Table 5.1: General Results from TIDE for the Manicouagan-Montreal System Design

	AC or DC	Volt.	Number of		Compensation			Performance: TOV	Performance: Line Loading		Performance: Loss	Performance: Term.	Costs (in 1991 dollars): Lines	Costs (in 1991 dollars): Rest of	Costs (in 1991 dollars): Loss	Costs (in 1991 dollars): Total
		(kV)	cir	SS	SC (%)	ShL (%)	SVC (MVAr)	(pu)	Thermal (%)	SIL (%)	(MW)	Losses (MW)	(M$)	Equip. (M$)	(M$)	(M$)
1	AC	735	3	1	0	9	959	1.6	26	80	109	-	1,080	303	218	1,601
2	AC	735	3	2	0	9	977	1.6	26	80	109	-	1,080	355	218	1,653
3	AC	735	2	1	45	0	2,213	1.6	39	121	164	-	720	648	328	1,696
4	AC	735	3	3	0	9	991	1.6	26	80	109	-	1,080	407	218	1,705
5	AC	735	2	2	45	0	2,155	1.6	39	121	163	-	720	680	326	1,726
6	AC	735	2	3	40	0	2,491	1.6	39	121	163	-	720	689	326	1,735
7	DC	600	2	-	-	-	-	-	42	-	109	75	559	879	368	1,806
8	DC	450	2	-	-	-	-	-	77	-	194	75	506	796	538	1,840
9	AC	735	4	1	0	18	0	1.6	20	60	82	-	1,440	389	164	1,993
10	DC	800	2	-	-	-	-	-	21	-	41	75	862	965	232	2,059
11	AC	735	4	2	0	18	122	1.6	20	60	82	-	1,440	458	164	2,062
12	AC	500	4	1	35	0	2,095	1.5	34	135	230	-	1,219	397	460	2,076
13	AC	1200	2	1	0	61	672	1.3	12	44	32	-	1,440	600	64	2,104
A	AC	500	3	1	60	0	2,322	1.5	46	180	306	-	914	628	612	2,154
B	AC	315	8	1	50	0	2,417	1.5	46	185	428	-	1,449	419	856	2,724
C	DC	250	4	-	-	-	-	-	50	-	315	75	1,056	942	780	2,778

The resulting transmission systems from TIDE are evaluated in the sections that follow for purposes of comparison from various points of view. These are voltage levels, number of circuits and substations, compensation levels, costs and system performance. In addition, one can compare the capability of future system expansion as well as the sensitivity of the designs with respect to fault types and costs. This detailed evaluation serves to illustrate the capabilities and the reasoning process of TIDE.

5.3.1 Voltage Levels

It can be clearly seen from Table 5.1 that the voltage of choice is 735 kV AC with the six lowest cost designs. There is a narrow spread of 8% in the costs separating these 735 kV AC systems which suggests that criteria other than cost should also be considered for the choice of the final design as described in the sections that follow.

From Table 5.1 it can also be seen that the other AC schemes are 26 to 67 percent costlier than the least expensive 735 kV AC system. There is no economic advantage therefore to consider a lower AC voltage (315 or 500 kV) or a higher one (1,200 kV). The 315 and 500 kV AC voltage schemes are more costly due to the high line losses. The 1200 kV AC voltage is not competitive because the minimum two circuits required for reliability are not sufficiently loaded.

Similarly, the DC schemes are 12 to 70 percent higher than the least-cost 735 kV system. The 250 kV and 800 kV DC alternatives are not competitive for the same reasons as the lower and higher AC voltages. The 450 kV and 600 kV DC systems are within the range of acceptability (12%) from the point of view of cost so that other considerations, such as supplying intermediate loads or system expansion, would be taken into account in selecting a final design.

5.3.2 Number of Circuits

Still referring to Table 5.1, the number of AC circuits required to supply 5,000 MW ranges from 2 (1200 kV AC) to 8 (315 kV). Higher voltage AC systems have relatively light line loadings (12% for 1,200 kV AC) to moderately loaded lines at the lower voltages (46% for 315 kV AC). The loading per circuit decreases with an increase in the number of circuits and, as a result, the line section outage contingency becomes less severe. The interaction between the number of circuits and the amount of series compensation can be seen by comparing systems 1 and 3 where one 735 kV line was replaced by the addition of 45% series compensation. The series compensation also improves the TOV performance by electrically shortening the line length. The series compensation, however, causes higher line loading, an increase from 26% to 39%, and more severe voltage regulation at heavy loads requiring about 2.3 times the amount of SVC.

The DC system line loading tends to be much higher than that of the AC systems. The number of DC bipoles range from 2 (450-800 kV DC) to 4 (250 kV DC) circuits. Additional circuits are not required as the DC systems do not have the stability limitations of AC systems. Thus, the line loadings range from 21% (800 kV DC) to 77% (450 kV DC). The limitations of this DC system are the constraints placed on the terminals. There is sufficient capacity in the lines to supply the complete load with one 800 kV DC circuit but this is not considered due to its unreliability (the loss of 1250 MW or one pole). If the maximum terminal size for 250 kV DC was increased, then the number of bipoles would drop to three and the line loading would increase to 67%. However, this system is still uneconomical when compared with the medium voltage levels. DC transmission is not well suited for this power and distance. The usage of types of transmission and various voltage levels is further discussed in section 5.8.

As the transmission line length increases, the line voltage regulation becomes more important than the thermal rating of the line. A measure of the AC line loading is the surge impedance loading (SIL). Table 5.1 shows the percent line loading as a function of the SIL ranging from 44-185%. Values exceeding 100% indicate that there will be a voltage drop across the line, as can be seen in designs 3, 5, 6, 12, A and B ranging from

Table 5.2. Performance Results from TIDE for the Manicouagan-Montreal System Design.

	AC/ DC	Volt. (kV)	Number of		Compensation			Performance						
								Static VAr Compensation			Stability Angles (degrees)			DC V. Drop (kV)
			cirs	SS	SC (%)	Sh L (%)	SVC (MVAr)	Stability	Heavy Load	Light Load	Steady-State	Fault Cleared	Max. perm. Swing	
1	AC	735	3	1	0	9	959	0	959	-585	51	89	120	-
2	AC	735	3	2	0	9	977	0	977	-650	52	79	125	-
3	AC	735	2	1	45	0	2,213	0	2,213	-281	46	105	115	-
4	AC	735	3	3	0	9	991	0	991	-686	52	75	127	-
5	AC	735	2	2	45	0	2,155	0	2,155	-330	46	81	126	-
6	AC	735	2	3	40	0	2,491	0	2,491	-246	48	81	125	-
7	DC	600	2	-	-	-	-	-	-	-	-	-	-	13
8	DC	450	2	-	-	-	-	-	-	-	-	-	-	18
9	AC	735	4	1	0	18	0	0	0	-1,277	43	60	138	-
10	DC	800	2	-	-	-	-	-	-	-	-	-	-	7
11	AC	735	4	2	0	18	122	0	112	-1,253	43	58	140	-
12	AC	500	4	1	35	0	2,095	0	2,095	-11	55	104	115	-
13	AC	1200	2	1	0	61	672	0	672	-746	36	62	135	-
A	AC	500	3	1	60	0	2,322	0	2,322	-90	48	87	125	-
B	AC	315	8	1	50	0	2,417	0	2,411	-25	56	96	121	-
C	DC	250	4	-	-	-	-	-	-	-	-	-	-	16

Note: These values depend on the accuracy of the equal-area criteria and the assumptions of an infinite bus for the heavy and light loading conditions. A tolerance of 5% and 230 MVAr's was used in the series capacitance and SVC calculations respectively.

121-185%. When line loadings exceed the line's SIL, large amounts of SVC are required to maintain a flat voltage profile as can be seen in Table 5.2.

TIDE provides a range of designs with various system loadings. Depending on the purpose of the design, different line loadings may be acceptable. Usually expandability and simplicity of design shift initial AC designs away from highly compensated lines with higher line loading to comparable designs with one or more additional circuits. The important point is that TIDE can take these considerations into account by varying the pertinent parameters according to the desired performance requirements (see section 5.3.9).

5.3.3 Number of Substations

For the AC systems, TIDE automatically investigates the effect of increasing or decreasing the number of substations for each base design. This influences the compensation distribution as well as the severity of line section outages. The benefits of adding substations to the base design, such as the ability to supply intermediate loads, are not explicitly considered in TIDE. Nevertheless, if there is foreseen need of future intermediate substations, this requirement can be represented by specifying a minimum number of substations.

Adding substations to a design marginally reduces the severity of the post-fault line-section loss as the faulted section is shorter. This observation is reflected in designs 1, 2 and 4 as well as 9 and 11 of Table 5.2 where a small reduction in the fault clearing angles can be seen with the addition of substations. As these designs are very stable for a single-phase fault, the addition of a substation does not significantly change the system dynamics.

In the steady-state operation, additional substations may require marginally more compensation to maintain flat voltage profile as the voltage is being controlled at more points along the transmission line. Thus, an additional substation increases the system cost

Table 5.3: Cost Results from TIDE for the Manicouagan-Montreal System Design in 1991 Dollars.

								Costs (in 1991 M$)							
	AC/ DC	Volt. (kV)	Number of		Compensation			Lines	Compensation			TF	Sub-Stations/ Terminal	Losses	Total
			cirs	SS	SC (%)	Sh L (%)	SVC (MVAr)		Series	Shunt	SVC				
1	AC	735	3	1	0	9	959	1,080	0	8	79	120	96	218	1,601
2	AC	735	3	2	0	9	977	1,080	0	8	83	120	144	218	1,653
3	AC	735	2	1	45	0	2,213	720	330	0	134	120	64	328	1,696
4	AC	735	3	3	0	9	991	1,080	0	8	87	120	192	218	1,705
5	AC	735	2	2	45	0	2,155	720	330	0	134	120	96	326	1,726
6	AC	735	2	3	40	0	2,491	720	293	0	148	120	128	326	1,735
7	DC	600	2	-	-	-	-	559	-	-	-	-	879	368	1,806
8	DC	450	2	-	-	-	-	506	-	-	-	-	796	538	1,840
9	AC	735	4	1	0	18	0	1,440	0	22	119	120	128	164	1,993
10	DC	800	2	-	-	-	-	862	-	-	-	-	965	232	2,059
11	AC	735	4	2	0	18	122	1,440	0	22	124	120	192	164	2,062
12	AC	500	4	1	35	0	2,095	1,219	127	0	98	92	80	460	2,076
13	AC	1200	2	1	0	61	672	1,440	0	157	107	208	128	64	2,104
A	AC	500	3	1	60	0	2,322	914	367	0	109	92	60	612	2,154
B	AC	315	8	1	50	0	2,417	1,449	182	0	101	72	64	856	2,724
C	DC	250	4	-	-	-	-	1,056	-	-	-	-	942	780	2,778

not only due to the components of the substation but also due to the extra VAr requirements needed to maintain the voltage profile. Additional substations, for this design, cannot be justified based on dynamic or steady-state operation so that costs (see Table 5.3) would have to be justified on the basis of having to supply future system loads.

Multiterminals are necessary to supply intermediate loads in a DC transmission system. Multiterminals are not considered in TIDE due to their complexity of operation but may be accounted for by adding the cost of the intermediate terminal to the final cost of the point-to-point design. In the Manicouagan system, an additional substation at Lévis would have to be added to supply local loads and thus a DC system would be even less attractive economically.

5.3.4 Compensation

Capacitive series compensation is used in AC designs to improve voltage and stability performance. In the designs generated by TIDE, series compensation is used in the 500 kV and 315 kV AC voltage levels as well as in the two-circuit 735 kV system. Comparing various designs in Table 5.1, it can be seen that series compensation can replace transmission lines. For example, in the 735 kV AC system (design 3), 45 % series compensation as well as about 1,700 MVAr of SVC replaces one of the three lines of design 1. Similarly for the 500 kV AC voltage level, comparing designs A and 12, 15% series compensation with about 1,200 MVAr of SVC replaces one of the five 500 kV lines.

The maximum series compensation of 60 % was required in the 500 kV, 3 circuit design (A). The 315 kV, 8 circuit system, (design B), also required a large amount of series compensation at 55%. For this medium transmission length of 600 km, the high degree of series compensation necessary does not result in good designs as the cost of compensation and losses exceed the line costs and the resulting designs are obviously not economical (see Table 5.3). Although TIDE considers and develops such transmission systems, it readily shows they are uneconomical. They are generated as requested by the design criteria and are only of interest for comparison purposes and to ensure a complete coverage of the design search space.

Shunt reactor compensation is used to control the temporary overvoltage, TOV (see section 3.3). As the TOV criterion was relaxed to permit the removal of some shunt reactors at heavy load, the rating indicated by TIDE will be underestimated. Table 5.1 shows shunt reactor requirements of 0 to 61 %. The TOV increases with the number of the lines while the transformer reactance remains constant, thus requiring more shunt compensation. Due to the high TOV design criterion, the shunt reactor compensation necessary to maintain flat voltage profile for light loading is inadequate and must be supplemented by the more expensive SVC. Thus, as shown in Table 5.2, large amounts of reserve SVC's are required for light loading conditions. This will tend to overestimate the SVC costs of the lightly loaded lines, but as the cost of all the SVC is only 4 to 8% of the total cost, the small difference is not considered significant for the purposes of this study. The removal of the shunt reactors at heavy load is not a good design practice as other equipment, such as sacrificial arresters, would be required to control the TOV. The actual amount of shunt reactance can be determined by restoring the original TOV design criterion in TIDE. The compensation costs can then be modified to reflect this refinement.

For this particular transmission corridor, the stability criterion of a single-phase fault is not a critical factor in determining the SVC rating. It can be seen in Table 5.2 that maintaining a flat voltage profile with one line section out is a much more important condition when rating the SVC than the stability criterion since, during the fault, the flat voltage profile criterion is relaxed to 0.6 p.u. It may be possible to reduce some of the large amounts of SVC required for flat voltage profile with additional series compensation. TIDE can study these possibilities as sensitivity cases but its present design methodology is to restrict the amount of required series compensation to avoid problems associated with high levels of series compensation. Of course, TIDE could eventually be altered to incorporate choices in the design philosophy so that instead of restricting the level of series compensation, a more balanced use of SVC is possible.

5.3.5 Costs

In addition to the basic characteristics of the system design described in Table 5.1, TIDE provides a summary of the cost breakdown as another means of comparing designs. The overall costs of Table 5.1 have been broken down into line, additional equipment and transmission loss costs. The additional equipment consists of compensation, transformers and substations for AC systems and terminal costs for DC systems. An even more detailed component cost breakdown for each system is provided in Table 5.3. The cost of each component as a function of the total cost provides an indication of how the money is being apportioned, its reasonableness and various tradeoffs.

For example, the series capacitance of design 3 replaces the additional line of design 1. The cost of a single 735 kV line is 360 M$. On the other hand, the equivalent change in equipment cost to be made to the remaining two transmission lines due to the increase in series and SVC compensation and the reduction in shunt compensation and substation costs is 322 M$. The net capital cost savings of 38 M$ is however overshadowed when compared to the 110 M$ increase in transmission losses. Thus, the cost tradeoffs in selecting a final design are readily available in the cost summaries of TIDE. In the designs summarized in Table 5.3, the line costs tend to be the most expensive component for the most economical AC systems.

DC line costs are substantially less than the AC line costs due to the fewer number of conductors and lines. This cost savings is offset, however, by large terminal costs and higher losses as seen in Table 5.1.

5.3.6 System Performance

The results of TIDE enable design comparison not only based on economics but also on system performance. Even though the systems have been based on good design practices, due to the large number of possible variations in the design parameters, the various design alternatives still possess performance characteristics that may influence the final choice of a transmission system. System performance gives an indication of system behaviour but is not directly reflected in the overall system cost. The system performance summarized in Table 5.2 provides information about AC stability, temporary overvoltages, line loading as well as system angles. In addition, the real and reactive power generated at the sending and receiving ends of the line is calculated by TIDE as part of the system performance results . In DC designs, the performance is measured in terms of line loading and voltage drop across the line.

It can be seen, for example, in Table 5.2 that the 2-line 735 kV designs (3, 5 and 6) require high levels of SVC to maintain the voltage profile during heavy load, whereas design 1 with three lines is able to more naturally maintain the voltage profile.

As stability angles also provide important performance information, TIDE calculates the system angles in steady-state, the angle at which the fault is cleared and the maximum first swing angle. Although the steady-state angle across the system is an important consideration, the dynamic performance may outweigh this. Comparing designs 1 and 3 of Table 5.2, it can be seen that despite having a smaller steady-state angle, design 3 is much less stable when comparing the fault clearing times. Design one even has a margin of 31° whereas design 3 only has a stability margin of 10°. Overdesign can also readily be seen in design 13 as its stability margin is 73° and it has the lowest steady-state system angle.

The voltage drop for the DC systems range from 7 to 16 kV or 1 to 6% respectively, well within the 10% maximum specified criterion.

5.3.7 Comparison with the Hydro-Québec System

The ensuing discussion will compare the Manicouagan designs suggested by TIDE with those discussed in a Hydro-Québec (HQ) report entitled "Economics and System Performance, E.H.V. Symposium" [71]. This report outlines planning decisions, design characteristics and criteria, as well as the costs of the various alternative designs considered for the Manicouagan transmission corridor. The four main transmission system designs (HQ1-HQ4) considered in the report are summarized in Table 5.4 and enable a comparison of TIDE's design methodology with that used by planning engineers. Note that the designs considered by the HQ engineers correspond to the designs 1, A and B of Table 5.1. Also note that for the cost data assumed in this study, designs A and B of Table 5.1 were *not* among the least expensive designs selected by TIDE. They are, however, included here to compare them with the HQ selections.

HQ's preliminary economic evaluation indicated that the system voltage level should be at least 500 kV. Higher voltage levels were also considered to ensure system flexibility for future expansion. A further discussion of the flexibility of several Manicouagan system designs can be found in section 5.3.9. The HQ report tried to equalize the stability of each system by adding series compensation to adjust the system angle as this was one of the criteria used in preliminary design by the HQ engineers. Subsequent stability studies indicated that the 315 kV system was the most stable as the post-fault N-1 criterion on an 8-line system was easily satisfied.

TIDE also concurs with the necessity of using voltage levels greater than 500 kV based on an economic evaluation. As TIDE provides a wide range of system designs, the system planner may readily choose a system with the desired characteristics whether they be flexibility, stability or reliability. Systems in TIDE are equalized not through steady-state system angles but by ensuring that the system is stable to a specified system fault through the addition of series compensation, SVC or lines.

Despite the difference in design philosophies, Table 5.4 shows remarkably similar system characteristics for the same voltage levels. Small differences in series compensation can be attributed to differences in stability modelling, a 600 MW intermediate load at Lévis (not modelled by TIDE) and the slightly higher voltage level of HQ2. Differences in losses are primarily due to HQ's inclusion of transformer losses and the use in TIDE of somewhat different conductors.

The costs used in this section were adjusted to match those used in the 1966 Manicouagan study [71], as these unit costs were significantly lower than those available in the default database of TIDE (Appendix B). With these adjusted costs, it is interesting to note that the 500 kV design was then slightly less expensive than the 735 kV design which is an opposite conclusion to that shown in Table 5.1. The 1966 HQ costs result in a much narrower range among the various design costs and are used in the design comparison shown in Table 5.4. These differences are due in part to the relatively inexpensive cost of losses in 1966 (140 $/kW compared to 2000 $/kW in 1991) as well as to a decrease in cost of the 735 kV equipment due to the maturing of EHV technology.

The line costs of HQ and TIDE, shown in Table 5.4, are identical as both analyses used the same overall line length. It should be noted, however, the overall line costs shown in Table 5.4 do not include the extra costs associated with the river crossings as this type of cost is not explicitly included in TIDE. Comparing the cost of equipment other than line costs, it can be seen that TIDE's costs are consistently higher than those of the HQ report. This is due to the additional spare transformers and SVC equipment included in TIDE. Spare transformers are included at both sending and receiving ends of the transmission line in TIDE, whereas the HQ study only placed spare transformers at the loads. The additional spares provided by TIDE translate into higher reliability, a criterion not explicitly considered by the HQ study.

The amount of series capacitance for designs HQ1 and HQ2 differs slightly from the HQ study which only affected the overall cost marginally. In addition, as a flat voltage profile is maintained in TIDE's designs, this requires some SVC compensation thereby also raising the rest-of-equipment costs.

In conclusion, for the Manicouagan system, TIDE was able to consider and develop the systems deemed important by HQ's system planners. The resulting system characteristics are very similar and quite acceptable for preliminary transmission design. The overall system costs of the designs proposed by TIDE compare favourably with those

Table 5.4: Results of Hydro-Québec's Manicouagan-Montreal Transmission Study Compared to TIDE Using 1966 Dollars.

Design Name	Source	AC or DC	Volt. (kV)	Number cirs	Number SS	SC (%)	Perf. Loss (MW)	Costs (in 1966 dollars) Equipment Lines (M$)	Equipment Rest of Equip. (M$)	Equipment Total Equip (M$)	Losses (M$)	Total (M$)
HQ1	HQ	AC	315	8	1	55	495	134	46	180	69	249
	TIDE (B)					50	428	134	85	219	60	279
HQ2	HQ	AC	525	3	1	*60/31	272	130	66	196	38	234
	TIDE (A)		500			60	233	130	107	237	32	269
HQ3	HQ	AC	650	3	1	10	180	131	65	196	25	221
HQ4	HQ	AC	735	3	1	0	163	163	66	229	23	252
	TIDE (1)					0	109	163	86	249	15	264

* Manicouagan-Levis/Laurentides 60%, and Levis/Laurentides-Montreal 31% series compensation.
The "HQ" is based on "The Choice of 735 kV Transmission Economics and System Performance". [71]

(1),(A),(B) Indicate the design number of TIDE's results as shown in Table 5.1.

suggested by the HQ study. Differences in design criteria account for the main discrepancies in the cost results.

5.3.8 Fault Type Sensitivity Analysis

The previous analysis is based on a single-phase (1ϕ) fault design criterion. When a more severe three-phase (3ϕ) fault criterion is used, most of the systems require more compensation to maintain stability. A comparison of the systems designed for 1ϕ or 3ϕ faults is summarized in Tables 5.5 and 5.6. Designs 9, 11 and 13 are sufficiently stable to withstand a 3ϕ fault without any changes. The other designs required up to 25% more series compensation and up to 1,000 MVAr of SVC depending on the case. Some systems have increased series compensation but decreased SVC whereas others retain the series compensation but require more SVC.

The design differences can readily be seen by comparing the total costs as shown in Table 5.5. The overall ranking of the designs remains fairly constant except for designs 3 and 12 which are more costly to stabilize since they have less stability margin to begin with. Even for a 3ϕ fault, 735 kV is still the voltage of preference and the present system (design 1) with 25 % series compensation is the most economical preliminary design.

Table 5.6 shows the stability angles for the systems generated for 1ϕ or 3ϕ faults (shown in Table 5.5). A reduction of the steady-state angles is observed on those systems with additional series compensation (designed for a 3ϕ fault). The increase in the power transfer capabilities of design 1 through series compensation is shown in Figure 4.9. The fault-clearing angles of these systems are much larger for a three-phase fault than for the less severe single-phase fault. The system angles as well as the stability equal-area diagram of design 1 is shown in Figure E.5.

TIDE enables the user to examine a wide variety of changes in the fault type design criterion and observe their effect on particular designs as well as on the overall system cost. The power system planner is then able to determine if the extra equipment

Table 5.5: Results of TIDE's Manicouagan-Montreal AC Designs Fault Comparison.

				Compensation					Costs (1991 M$)		
AC Design	Volt. (kV)	Number of		SC (%)		SL (%)	SVC (MVAr)		Total		Diff.
		cirs	SS	1ϕ	3ϕ		1ϕ	3ϕ	1ϕ	3ϕ	Δ
1	735	3	1	0	25	9	959	228	1,601	1,683	82
2	735	3	2	0	20	9	977	440	1,653	1,727	74
4	735	3	3	0	15	9	991	560	1,705	1,763	58
3	735	2	1	45	60	0	2,213	1,167	1,696	1,772	76
5	735	2	2	45	55	0	2,155	1,473	1,726	1,777	51
6	735	2	3	40	55	0	2,491	1,472	1,735	1,811	76
9	735	4	1	0	0	18	0	0	1,993	1,993	0
11	735	4	2	0	0	18	122	122	2,062	2,062	0
13	1200	2	1	0	0	61	672	672	2,104	2,104	0
12	500	4	1	35	55	0	2,095	937	2,076	2,114	38
A	500	3	1	60	60	0	2,322	3,500	2,154	N/A	N/A
B	315	8	1	50	60	0	2,417	1,726	2,724	2,742	18

Note: Designs ranked according to their three-phase cost. Shaded designs indicate changes in the design cost ordering from the single-phase cost.

Table 5.6: Performance Summary of TIDE's Manicouagan-Montreal AC Designs Fault Comparison.

AC Design	Volt. (kV)	Number of cirs	Number of SS	Stability Angles (degrees): Steady-State 1ϕ	Steady-State 3ϕ	Fault Cleared 1ϕ	Fault Cleared 3ϕ	Maximum Swing 1ϕ	Maximum Swing 3ϕ
1	735	3	1	51	43	89	122	120	135
2	735	3	2	52	45	79	117	125	136
4	735	3	3	52	47	75	121	127	135
3	735	2	1	46	38	105	129	115	136
5	735	2	2	46	41	81	123	126	136
6	735	2	3	48	41	81	110	125	139
9	735	4	1	43	43	60	106	138	138
11	735	4	2	43	43	58	101	140	140
13	1200	2	1	36	36	62	108	135	135
12	500	4	1	55	43	104	120	115	138
A	500	3	1	48	N/A	87	N/A	125	N/A
B	315	8	1	56	49	96	133	121	139

Note: Designs ranked according to their three-phase cost.
Shaded designs indicate changes in the design ordering.

is worth the additional expense in terms of improved system performance. This concept is expanded in section 5.6.

5.3.9 Design Flexibility

Flexibility is an additional factor which should be considered in choosing the best preliminary system design. The reader is reminded that flexibility is the capability to expand easily and economically to accommodate increased generation and demand. This is especially important when a number of system design costs are within a narrow range and system expansion is foreseen.

AC systems can be expanded by adding new circuits or extra series and shunt compensation. In the example that follows, the concept of design flexibility is illustrated by the addition of series compensation to an existing design in order to accommodate additional load. This is a relatively inexpensive way of increasing the power transmission capability and is preferable to the addition of circuits. Related costs, such as changes to the protection system, are not considered in this study. The purpose of this flexibility example is to demonstrate how TIDE calculates the level of additional power that each system can transmit and at what cost. Power levels up to twice the initial transmitted power are considered.

In these tests, the number of lines and substations as well as the minimum required amount of shunt reactance was kept constant. The amount of series and SVC compensation as well as the transformer ratings were increased to meet the expanding power transmitted from the initial value of 5,000 MW to 10,000 MW. The same design criteria were used for this study as in the initial 5,000 MW cases.

The following five representative design alternatives from Table 5.1 were considered: one 500 kV design (12) with 4 lines, three 735 kV designs (3,1,9) with 2,3 and 4 lines respectively and one 1200 kV design (13) with 2 lines. The results of the cost versus MW transmitted are shown in Figure 5.2.

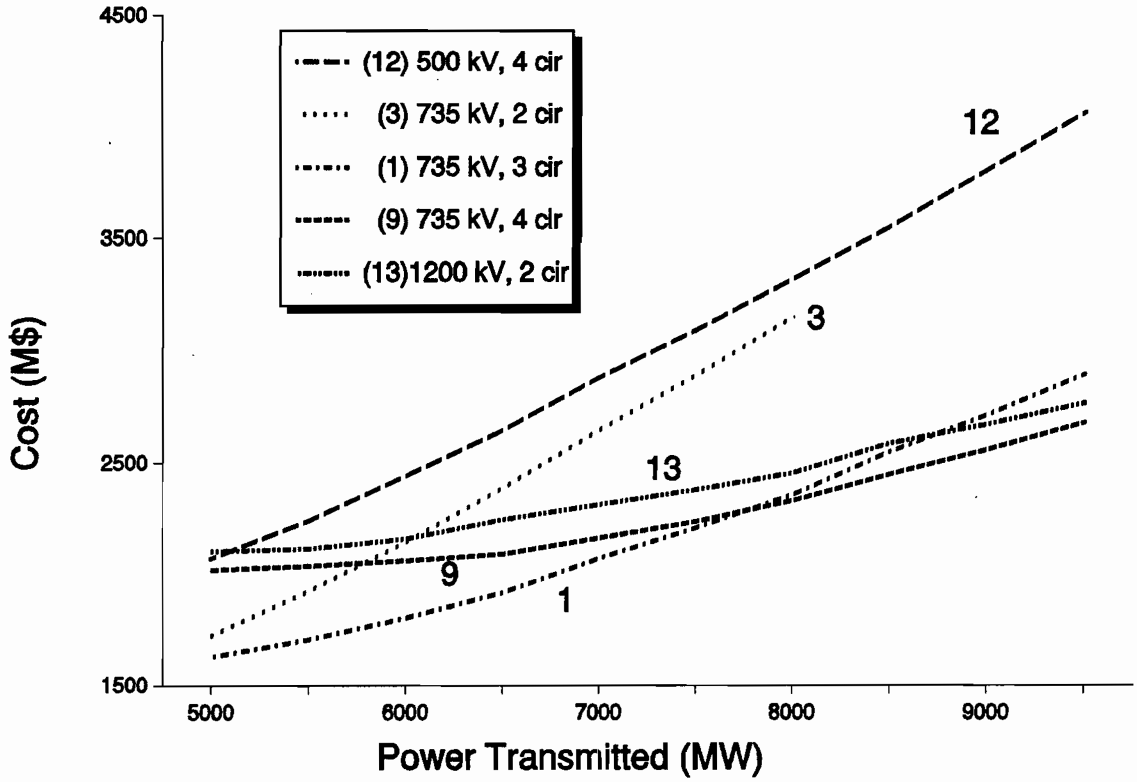


Figure 5.2: Manicouagan System Expansion

As Figure 5.2 shows, all the designs were able to transmit the full 10,000 MW except the two circuit-735 kV design (3) which could only transmit 8,000 MW without exceeding the design criteria. Although this design appeared to be very attractive for the initial power level of 5,000 MW, it became the second most expensive for values greater than 6,000 MW. The 500 kV design (12) quickly became the most expensive design and can be discarded as not being a suitable voltage level for this combination of power and distance when considering system expansion.

In the remaining three designs there are two breakpoints where the design's costs cross. The three-line 735 kV system remains the most economical for powers up to 7,500 MW. At this point, the 4 line-735 kV system becomes the most economical. Additional sensitivity analyses can be performed using TIDE to determine up to what point it is most economical to add an additional line to a system with a given compensation level. It is reassuring to realize, that despite the necessity of adding a transmission line, the 735 kV voltage level is still the least costly alternative. At powers greater than 8,500 MW it can be seen that 1,200 MW is becoming more economical as it is less expensive than the 3 line-735 kV design (1). Practically, however, before a 2-line-1,200 kV system would be considered, additional reliability measures would have to be analyzed.

TIDE can readily perform generalized sensitivity studies on most system parameters, examples of which are: transmitted power, transmission distance, fault duration, equipment cost, reliability and maximum series compensation. The above mentioned design flexibility study is a specific example of a one dimensional sensitivity analysis where the transmitted power is varied for a given system topology. Five sensitivity simulations, one for each transmission system, were performed using TIDE to generate Figure 5.2. TIDE's sensitivity menu is shown in Figure A.19. To perform a sensitivity study, the user specifies the parameters (class and property) to be varied, the step size and number of steps to be studied. TIDE also has the capability of readily performing two dimensional sensitivity studies, an example of which is discussed in section 5.8. These sensitivity analyses can be performed for individual systems or for generalized system design.

5.3.10 Cost Sensitivity Analysis

Cost sensitivity analysis illustrates the effect on the overall costs due to variations in component and generation costs. The hierarchical class structure of TIDE's equipment database enables cost sensitivity studies to be performed at various levels ranging from individual components and equipment types to all equipment. This section illustrates the sensitivity of the Manicouagan system total cost to a 25% increase in the cost of losses, lines and other equipment. Table 5.7 contains a summary of the base system costs, the new system costs including the 25% increase and a new system ranking based on the cost sensitivity. Systems A, B and C are not ranked among the other designs as they are much more expensive and were only shown for comparison purposes. Designs A and B were originally examined by HQ planners and design C is the least-cost 250 kV DC design.

	AC/DC	Volt. (kV)	Number of		Compensation			Original Cost	Cost Sensitivity (in 1991 dollars): 25 % Increase in the Cost of Losses		25 % Increase in the Cost of Lines		25 % Increase in Cost of Other Equipment	
			cirs	SS	SC (%)	Sh L (%)	SVC (MVAr)		Cost (M$)	Rank	Cost (M$)	Rank	Cost (M$)	Rank
1	AC	735	3	1	0	9	959	1,601	1,655	1	1,871	1	1,676	1
2	AC	735	3	2	0	9	977	1,653	1,707	2	1,923	5	1,741	2
3	AC	735	2	1	45	0	2,213	1,696	1,778	4	1,876	2	1,857	4
4	AC	735	3	3	0	9	991	1,705	1,759	3	1,975	8	1,806	3
5	AC	735	2	2	45	0	2,155	1,726	1,807	5	1,906	3	1,895	5
6	AC	735	2	3	40	0	2,491	1,735	1,816	6	1,915	4	1,907	6
7	DC	600	2	-	-	-	-	1,806	1,898	7	1,945	6	2,025	7
8	DC	450	2	-	-	-	-	1,840	1,975	8	1,966	7	2,039	8
9	AC	735	4	1	0	18	0	1,993	2,034	9	2,353	10	2,089	9
10	DC	800	2	-	-	-	-	2,059	2,117	11	2,274	9	2,300	13
11	AC	735	4	2	0	18	122	2,062	2,103	10	2,422	N/A	2,176	11
12	AC	500	4	1	35	0	2,095	2,076	2,191	13	2,380	11	2,174	10
13	AC	1200	2	1	0	61	672	2,104	2,120	12	2,464	N/A	2,253	12
A	AC	500	3	1	60	0	2,322	2,154	2,307	N/A	2,382	12	2,310	N/A
B	AC	315	8	1	50	0	2,417	2,724	2,938	N/A	3,086	N/A	2,828	N/A
C	DC	250	4	-	-	-	-	2,778	2,973	N/A	3,042	N/A	3,013	N/A

Shaded cells indicate changes in the design ordering.

There is little effect on the ranking for a 25 % increase in the cost of losses. Systems with higher voltage levels or more circuits will be favoured by this increase in losses and may move up in the system rankings. For example, the 1200 kV system (design 13) moves from the 13th position to the 12th position as it has very low losses compared to the 4 line 735 and 500 kV systems (11 and 12). However, the sensitivity analysis with respect to losses does not significantly change the voltage and design of choice. In addition, designs 3 and 4 exchange rankings since the design 4 with three lines has significantly lower losses.

A 25% increase in the line costs has a much more significant effect on the system ranking. This is due to the high percentage of line costs in the overall system cost. Design 1 still remains the least expensive design and the four least expensive designs are still 735 kV. The DC designs, however, become more attractive as they have relatively low line costs compared to the AC systems.

The ranking of designs 3, 10 and 12 are changed when there are 25% increases in the equipment cost other than lines. The systems that are most sensitive to this type of analysis are AC systems with high degrees of compensation and all DC systems due to their high terminal cost. Similar to the other sensitivity studies mentioned above, the least cost designs remain the 735 kV designs.

Cost sensitivity analysis is automatically performed for each system design based on sensitivity ranges. Potential cost increments are entered for each individual component so that the cost range being studied reflects specific component characteristics. TIDE provides sensitivity tables for the cost of each component, the cost of system reliability as well as the cost of losses. If a broader scope of sensitivity analysis is required, the sensitivity analysis feature of TIDE can be used.

In conclusion, for the Manicouagan system, the systems of choice are not greatly influenced by sensitivity considerations with respect to fault type, load growth flexibility and unit costs. Thus, TIDE assures a thorough design process by not only providing information about the system costs and performance but also by enabling the user to perform sensitivity studies which ensure that the transmission system will remain competitive within possible changes in the design criteria or impact parameters.

5.4 Comparison with Other Existing Transmission Systems

Three Canadian transmission system designs, in addition to the Manicouagan system, were chosen to evaluate TIDE. The systems are the James Bay [72], Peace River [88] and Nelson River [27] corridors. The first two systems are AC while the third is a DC system which was installed in three phases. The main actual system characteristics as well as those designed by TIDE are discussed below.

For each transmission system the length, power transmitted and design criteria were specified to TIDE. A common equipment database described in Appendix B was used for all the system designs. AC and DC systems for all eight voltage levels were available for TIDE's consideration. A comparative summary of the actual system designs and the designs proposed by TIDE are shown in Table 5.8.

James Bay Corridor: 10,000 MW of hydro generation on the La Grande River in Northwestern Québec is connected to the main load centres in Montréal and Québec City by 5-735 kV AC transmission lines. The 1,000 km transmission system was completed in 1985 by Hydro-Québec. Switched reactors, sacrificial arresters, eight static compensators and two synchronous condensors were used for voltage control and to maintain stability for a single-phase fault. Shunt reactors, required for voltage control are switched out during heavy load operation. In the event of load rejection, substations were protected with sacrificial surge arresters [72]. This was modelled in TIDE by relaxing the TOV criterion.

Application of TIDE to the above network results in a least cost design concurring with the actual 5 line, 735 kV AC system.

James Bay Upgraded: The original stability design criterion has recently been upgraded from a single-phase to a three-phase fault in order to comply with the NPCC [79],[81],[80] requirements and thereby increase exports to the U.S. The more stringent stability criterion was met through the addition of 40% series compensation in all five lines from James Bay [72]. This new James Bay corridor system was also designed by TIDE using the same new stability criterion. The TOV constraints were also set to the original higher levels shown in Appendix B since the extra series compensation tends to supply the reactive power required by the shunt reactors during heavy load conditions. In this test case, TIDE tended to overestimate the compensation levels compared to the actual system. Thus, TIDE suggested either 49% series compensation (compared to 40% actually used) or higher SVC levels in order to stabilize the system for a three-phase fault. This can easily be explained by the conservative nature of the equal-area stability criterion.

TIDE also recommends several DC systems which are also economically attractive as shown in Table 5.8. However, as will be shown in section 5.6, these DC designs will prove to be less reliable than the AC alternatives. For this reason, even if the system were being built from scratch, the DC solution would not have been recommended.

Peace River: Running North-West in Eastern British Columbia, the Peace River transmission line connects 2,400 MW of hydro generation to a southern load centre some 900 km away. The two-circuit 500 kV AC system was energized in 1970. Transient stability proved to be the predominant problem in this system, requiring 50 % series compensation, generation shedding, braking resistors, high-speed line reclosure, high-response exciters and power-system stabilizers [27],[88].

It can be seen in Table 5.8 that the least expensive AC design recommended by TIDE is a two-circuit 735 kV system.

TIDE also recommends a two-circuit 500 kV AC system if the maximum series compensation is set to 62% without the necessity of implementing all the extraordinary stability measures present in the actual Peace River system. TIDE rejected the two-circuit system with only 50% series compensation since the system is almost at its steady-state limit while supplying full load with one line section out resulting in almost no stability margin. These observations concur with the discussion in reference [27] which indicated that special protection schemes (SPS) were required to maintain stability. TIDE does not model such schemes based on the principle that SPS should not be employed to cope with normal contingencies.

TIDE also recommends a three-circuit 500 kV AC solution which is cost competitive, uses only 40-45% series compensation, and results in a system with a good stability margin.

What TIDE does present to the system planner are designs which tend to be inherently more stable. However, the stability design criterion in TIDE can be modified to reflect the use of other stability measures (not modelled in TIDE) such as those used in the Peace River system by reducing the fault duration. What is important to note is that through the use of these stability measures, B.C. Hydro saved themselves the cost of an additional circuit. In their detailed design phase it must have been determined that the cost savings of the third line did not render the system too vulnerable. The advantage of a tool like TIDE at this stage of the planning process is that a wide spectrum of alternatives can be considered very rapidly and efficiently thus ensuring that no potentially better solution would have been overlooked. For example, other options suggested by TIDE are to increase the voltage level to 735 kV or use a DC system. The DC alternative however presents problems associated with multi-terminal operation as additional circuits join the main North-South transmission corridor.

Nelson River: The 3,667 MW Nelson river project exploits the hydro resources in northern Manitoba. The 900 km North-South DC transmission system was built in three stages corresponding to the hydro generator commissionings. First, a single ±463 kV DC bipole line with a capacity of 1,667 MW was commissioned in 1972, followed by a ±500 kV DC bipole line in 1978 with a transmission capacity of 2,000 MW. This line was operated at half its capacity (1,000 MW) until 1985 when all the generation of the Nelson River was completed and the 500 kV line reached its full capacity of 2,000 MW [27].

Although the staged development of a transmission system cannot be treated explicitly in the present version of TIDE, a system planner can quickly take the results of each of the three design phases and determine the preliminary design alternatives.

When considering AC alternatives, in order to obtain similar levels of reliability as the single-pole DC operation, two AC lines would be necessary. Thus, the utility would virtually be required to install the final AC system immediately, carrying the costs of the unused transmission line for 6 years when the second DC line was built. Two 500 kV AC transmission lines are a possibility with a marginal cost premium but the final system is not optimal and is more expensive than the 735 kV system. Thus, for such a staged project, the DC system has a clear advantage.

The DC designs suggested by TIDE indicate that either two 450 or 600 kV or a single 800 kV system are economical for the final system design. The 800 kV system would have been ruled out by reliability and technological constraints in 1972. Similarly, it would not be worth considering an increase in voltage level as the 600 kV system is marginally more expensive. Thus, TIDE concurs with the transmission design adopted for the Nelson River project.

Table 5.8: Comparison of TIDE with Existing Systems

Design	Actual Systems: AC or DC	Actual Systems: Volt. (kV)	Actual Systems: Number of Cir.	Actual Systems: Number of SS.	Actual Systems: Series Cap. (%)	Actual Systems: SVC (MVA)	TIDE: AC or DC	TIDE: Volt. (kV)	TIDE: Number of Cir.	TIDE: Number of SS.	TIDE: Series Cap. (%)	TIDE: SVC (MVA)	TIDE: Cost (1991 M$)
1) James-Bay (1ϕ fault)	AC	735	5	3	0	3000	AC	735 735	5 6	2-4 2	0 0	4520-5000 4520	4630-4768 5071
							DC	800 600 450	3 4 4	-	-	-	4455 4651 4877
2) James-Bay (3ϕ fault)	AC	735	5	3	40	3000	AC	1200 735 735	3 5 6-7	2-4 3-4 2-4	35-40 50 40	2400-2840 4519-5000 1254-5000	5437-5620 5216-5270 5644-5926
3) Peace-River	AC	500	2	2	50	0	DC	600 450 800	1 1 1	-	-	-	1075 1113 1247
							AC	735 500 500	2 3 2	1-3 1-3 2	35-45 45-50 62	218-695 226-369 1200	1572-1634 1760-1840 1794

Table 5.8 (Con't): Comparison of TIDE with Existing Systems

Design	Actual Systems					TIDE					
	AC or DC	Volt. (kV)	Number of Cir.	SS.	Series Cap. (%)	AC or DC	Volt. (kV)	Number of Cir.	SS.	Series Cap. (%)	Cost (1991 M$)
4) Nelson River 3,667 MW	DC	463 500	2	-	-	DC	800 450 600	1 2 2	-	-	1445 1893 1894
						AC	735 735 500	2 3 3	2-5 2-4 2-4	55 30 60	2075-2194 2267-2357 2437-2456
5) Nelson River 1,667 MW	DC	463	1	-	-	DC	450 600 800 250	1 1 1 2	-	-	897 905 1096 1432
						AC	500 735	2 2	1-4 1-4	50-60 5-25	1303-1334 1432-1475
6) Nelson River 2,667 MW	DC	463 500	1	-	-	DC	600 450 800	1 1 1	-	-	1131 1192 1294
						AC	735 500	2 3	1-4 1-4	40-50 50-60	1642-1709 1903-1951

It can be seen from these examples how TIDE can be used to design transmission systems. The design criteria may be adjusted through the input parameters of TIDE to match the desired characteristics of each system according to the philosophy of each utility. What can be seen is that TIDE allows the designer to examine a broad range of alternatives. In addition, TIDE provides a great deal of information about possible designs including cost, stability, compensation, AC/DC tradeoffs, expansion flexibility and sensitivity analysis. All of this information is a valuable aid to the transmission planner in reaching the final design choice.

5.5 Reliability Calculations

Transmission facilities are traditionally evaluated on the basis of the cost of equipment and losses. However, reliability is another important design criterion which cannot be ignored. TIDE contains a module which analyses in considerable detail the reliability of each design proposed by the reasoning process. In this section, a full example of this capability is demonstrated through one of the designs (design 1, Table 5.1) suggested by TIDE for the Manicouagan system.

An example of the failure tree of design 1 (Table 5.1) as provided by the interface of TIDE is shown in Figure 5.3. A single-line diagram of the network is shown in the upper right hand corner of the figure. The availability of each individual component, based on the individual component repair and failure rates (see Appendix B), is shown in the left hand column under the load-duration curve (LDC). The probability of being in each state is calculated using the equivalent reduced state failure and repair rates. The state probabilities are shown in Figure 5.3 and are the second row of numbers of each contingency level.

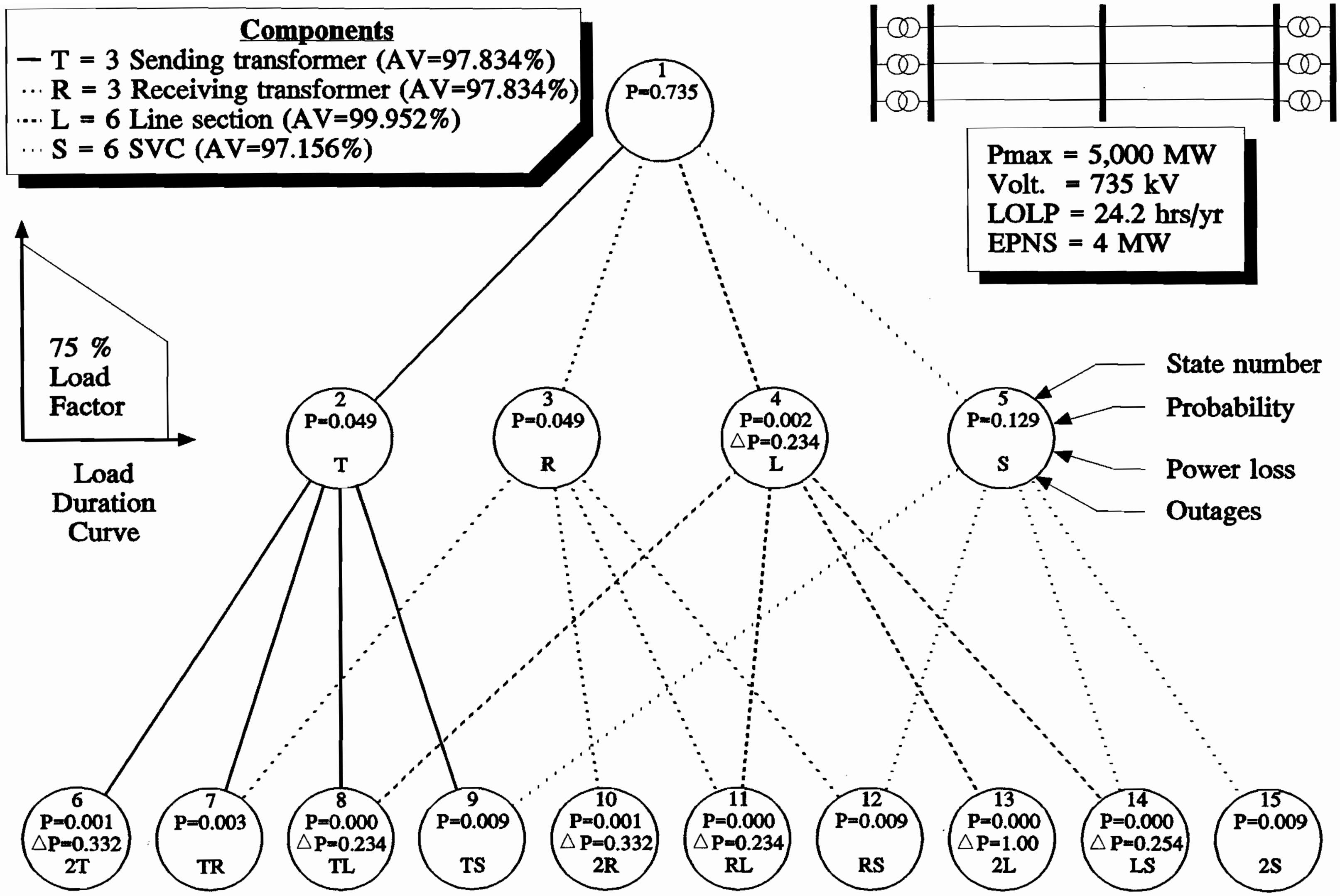


Figure 5.3: Base Design State Diagram.

The LDC used for the Manicouagan system reliability analysis is shown in the upper left hand corner of Figure 5.3. It was taken simply as a straight line with a load factor of 75% with a maximum and minimum power of 1 pu and 0.5 pu respectively.

Referring to Table 5.9, the system is in the intact state (state 1) 74% of the time. Thus, at any one time, there is a 26% probability that at least one element is out of service. Given the large number of elements in a power system, this is not unrealistic. It is for this reason that there are spare components, such as transformers and SVC's, built into the initial design.

There is also a relatively high probability (13%) of being in state (5) which is the loss of any SVC element. The reason for this high probability is the relatively low availability (97%) of SVC's. In contrast, the probability of having a single transformer out is 5% while the probability of having one single line section out is only 0.2%.

Each state may result in a loss of load due to static (power flow thermal limits) or dynamic considerations (power flow stability limits). As the intact systems are designed to meet an N-1 criterion (see section 3.3), there is no loss of load resulting from the failure of any single element. However, if the system is in a degraded state with one element out of service, it may be necessary to decrease the load in order to respect the N-1 criterion of security. The system has a single element out of service 23% of the time but only the loss of a single line section results in a load reduction of 23%, a situation which occurs with a probability of only 0.2%. Thus, the first contingency level does not add significantly to the system LOLP or EPNS which means that the overall system will see no loss of load due to transmission system outages for approximately 97% of the time. The remaining 3% of the time covers second and lower contingency levels with possible higher levels of loss of load.

Considering the second contingency level shown in Table 5.9, it can be observed that the probabilities of these states are relatively low but the corresponding loss of loads

Table 5.9: Manicouagan Reliability States.

State	Reliability Cause	Element out of Service: Tsf S	Tsf R	Line	SVC	State Probability (p.u.)	Cumulative (p.u.)	Loss-of-Load Δ P: Thermal (p.u.)	Stability (p.u.)
Intact System									
1		0	0	0	0	0.735354	0.735354		
First Level Contingency									
2		1	0	0	0	0.048838	0.784192		
3		0	1	0	0	0.048838	0.833030		
4	Line sect	0	0	1	0	0.002131	0.835161		0.234
5		0	0	0	1	0.129163	0.964325		
Second Level Contingency									
6	Send tsf	2	0	0	0	0.001081	0.965406	0.332	
7		1	1	0	0	0.003244	0.968649		
8	Line sect	1	0	1	0	0.000142	0.968791		0.234
9		1	0	0	1	0.008578	0.977369		
10	Load tsf	0	2	0	0	0.001081	0.978450	0.332	
11	Line sect	0	1	1	0	0.000142	0.978592		0.234
12		0	1	0	1	0.008578	0.987170		
13	Line sect	0	0	2	0	0.000003	0.987173		1.000
14	Line sect	0	0	1	1	0.000374	0.987547		0.254
15		0	0	0	2	0.009453	0.997000		

are considerably higher ranging from 0 for the loss of one transformer at both the sending and receiving ends to the complete system for the outage of two line sections (state 7). The system obviously cannot remain secure for the loss of the third parallel line section (state 13) since there are only three lines. This is a conservative approach followed in this example as the operator would not shut down the whole system in the event of the loss of two parallel power line sections but would still try to transmit power over the remaining line in this emergency condition.

TIDE carries out this type of reliability down to 4 contingency levels for a total of 66 states. The number of contingency levels and components is user specified and is limited only by the memory of the computer. This example is executed, including tables and graphs, by the present version of TIDE in less than 5 seconds.

The next section describes how TIDE makes use of the reliability calculations in the design process.

5.6 Reliability Considerations in Design

Reliability provides an additional dimension for comparing and ranking alternative designs [102]. Those not meeting the desired reliability standards could be removed from the list of acceptable designs. The remaining designs can be ranked by assigning an additional cost to system unreliability. Systems with lower total cost and higher reliability are clearly superior. However, systems which are less expensive and less reliable or more expensive and more reliable are difficult to compare unless one assigns some monetary cost to unreliability.

TIDE can present the reliability results in a graphical form, enabling a system planner to quickly compare the proposed system designs from the points of view of cost and reliability. Three methods of graphically representing the data are offered by TIDE: cost versus LOLP, cost versus EPNS and a sensitivity analysis of the cost of unreliability. The first two methods are used to screen designs based on a specified minimum reliability design criterion and to identify systems with similar cost/reliability characteristics. The third method permits system comparison including uncertainty in the cost of unreliability.

TIDE assigns a cost to unreliability in \$/MW, i.e. dollars per MW of average unserviced power which can be directly computed from the EPNS.

These ideas are illustrated through the Manicouagan system described in section 5.2. The reliability of the Manicouagan systems proposed by TIDE is given in Table 5.10 and graphically in Figures 5.4, 5.5 and 5.6. The reliability, by and large, does not affect the least cost ordering of the Manicouagan designs for a reliability cost equal to that of the generation cost (2000 \$/kW). This is true since the EPNS figures are generally relatively low due to the inherent security margin built into the design by TIDE. Designs 3 and 10, however, become marginally more expensive than the next ranked designs due to unreliability.

It can be seen in Figure 5.4 that there are groups of system designs with similar costs and reliability. A group of superior designs, with both low cost and high reliability, are located in the bottom left hand corner of the figure. These designs consist of 735 kV, two and three circuit AC systems. A second set of designs which stand out are the DC designs which are grouped at the right of the figure with high unreliability. Depending on the system planner's minimum acceptable reliability criteria, these DC designs might be excluded from any further consideration due to their high unreliabilities.

The 450 and 600 kV DC designs (8 and 7) are attractive due to their low capital costs but any minor change in the cost assigned to system unreliability can quickly make them more expensive. The third group of systems are the 1,200 and 500 kV AC systems as well as a 4 circuit 735 kV design. They have comparable reliabilities but are more expensive. The last group of systems (at the top left of the figure), due to their high costs, indicate that an inefficient voltage level is being considered. Similar groupings may be seen for the EPNS values as shown in Figure 5.5.

One of the main factors influencing the reliability of the Manicouagan systems is the number of circuits. The most reliable system is design B, a 315 kV AC system with

Table 5.10: Reliability Results of Manicouagan-Montreal Design Study

								Reliability		Costs (in 1991 dollars)		
	AC or DC	Volt. (kV)	Number of		Compensation			LOLP (hrs/year)	EPNS (MW)	System (M$)	Reliability (*) (M$)	Overall (M$)
			cirs	SS	SC (%)	Sh L (%)	SVC (MVAr)					
1	AC	735	3	1	0	9	959	27	5.	1,601	9	1,610
2	AC	735	3	2	0	9	977	21	3.3	1,653	6	1,659
3	AC	735	2	1	45	0	2,213	33	13.	1,696	25	1,721
4	AC	735	3	3	0	9	991	16	3.1	1,705	6	1,711
5	AC	735	2	2	40	0	2,155	41	18.	1,726	35	1,761
6	AC	735	2	3	35	0	2,491	50	22.	1,735	44	1,779
7	DC	600	2	-	-	-	-	410	62.	1,806	124	1,930
8	DC	450	2	-	-	-	-	450	68.	1,840	136	1,976
9	AC	735	4	1	0	18	0	16	3.1	1,993	6	1,999
10	DC	800	2	-	-	-	-	410	62.	2,059	124	2,183
11	AC	735	4	2	0	18	122	16	3.1	2,062	6	2,068
12	AC	500	4	1	35	0	2,095	11	0.6	2,076	1	2,077
13	AC	1200	2	1	0	61	672	27	11.	2,104	21	2,125
A	AC	500	3	1	60	0	2,322	15	1.4	2,154	4	2,158
B	AC	315	8	1	50	0	2,417	1	0.0	2,724	0	2,724
C	DC	250	4	-	-	-	-	428	36.	2,778	71	2,849

(*) Reliability costs based on the generation costs (2,000 $/kW).

Figure 5.4: Manicouagan Reliability Analysis - Cost Versus LOLP

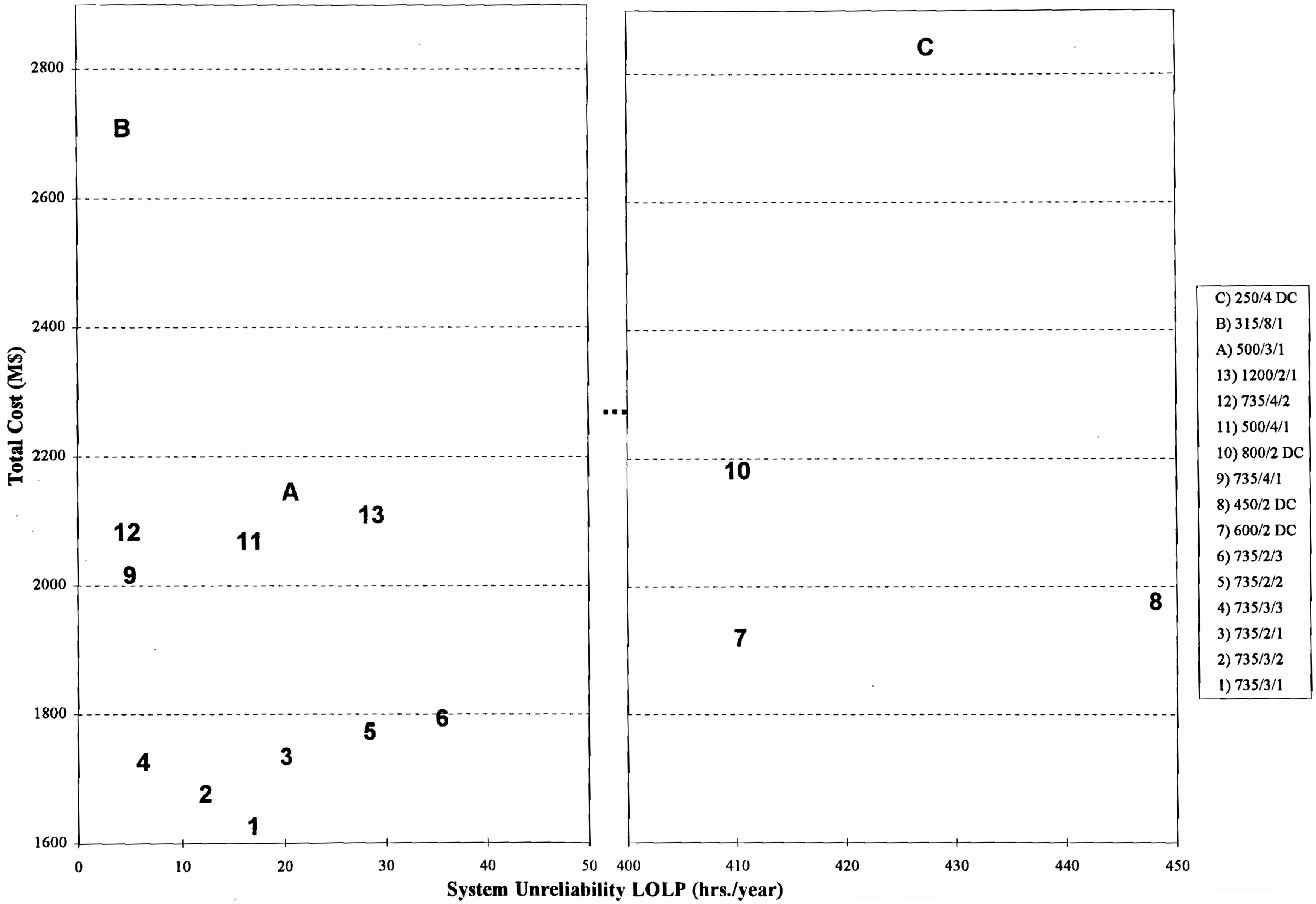


Figure 5.5: Manicouagan Reliability Analysis - Cost Versus EPNS

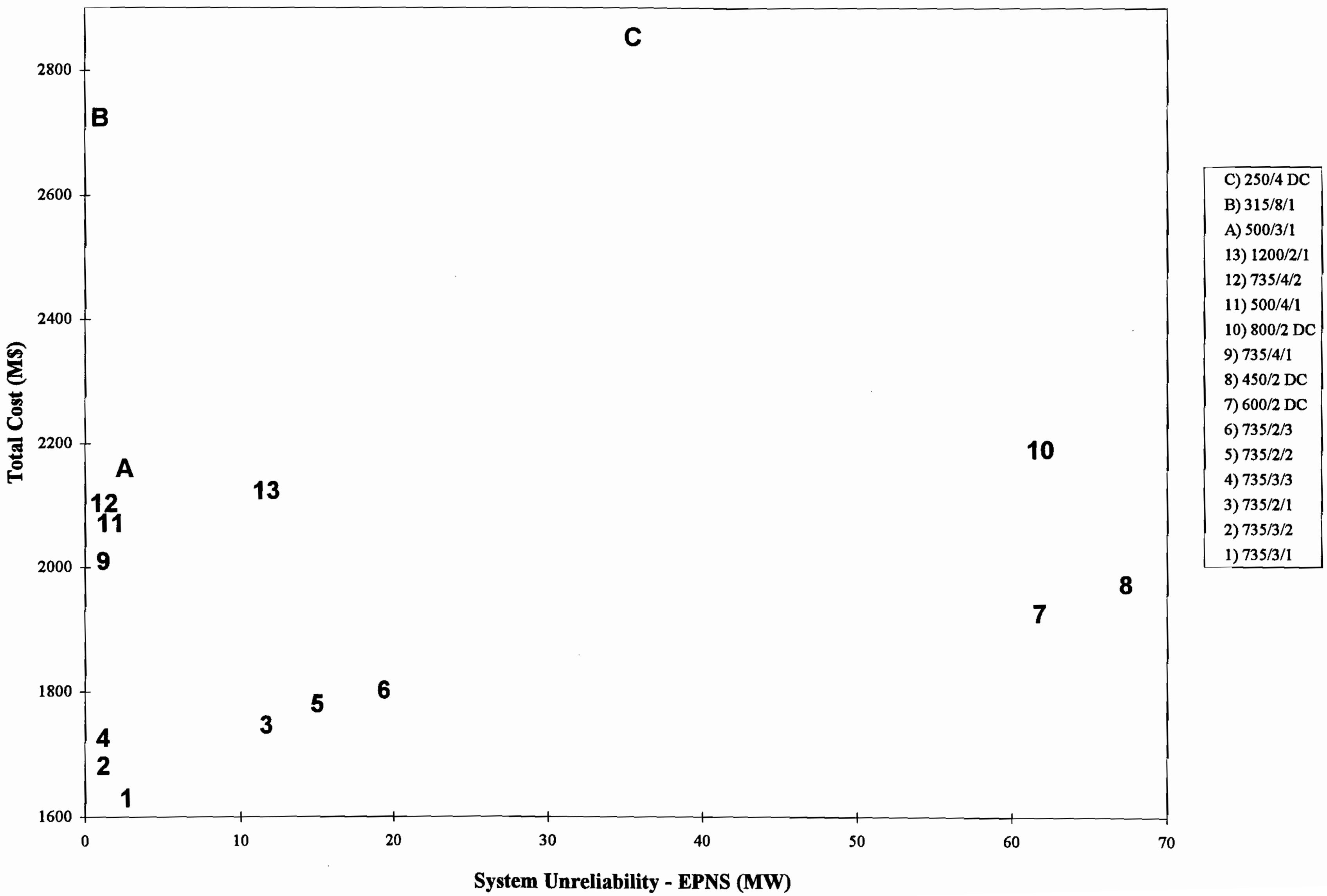
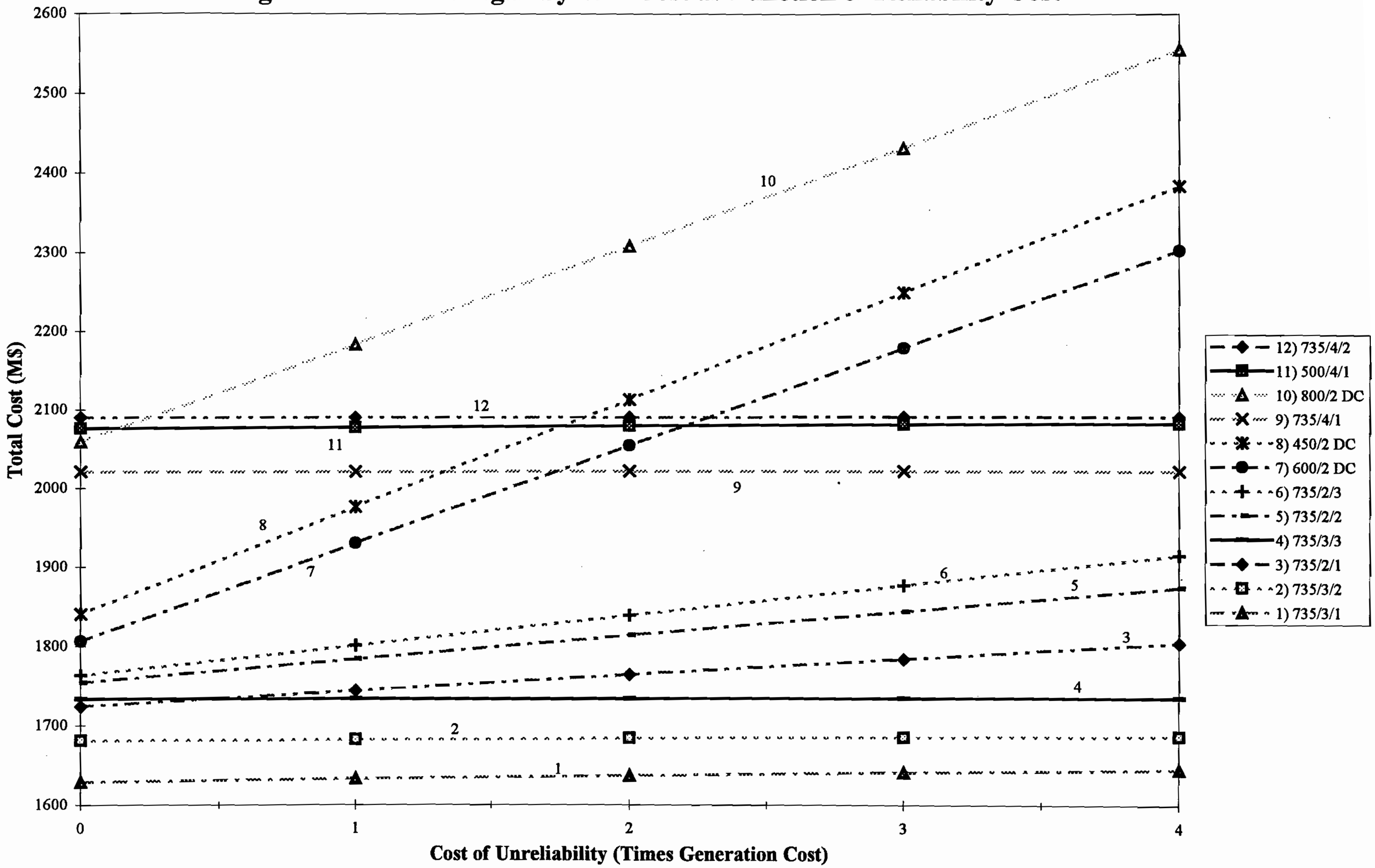


Figure 5.6: Manicouagan System Cost as Function of Reliability Cost



8 circuits while the least reliable are those with only 2 circuits. There is a premium for the high reliability systems but high cost does not necessarily ensure a reliable system.

The system reliability is less sensitive to variations in the number of substations in a design. Comparing designs 1, 2 and 3, small increases in system reliability can be observed as would be expected with increasing number of substations. However, comparing designs 3, 5 and 6 show the opposite trend due to changes, not only in the number of substations, but also in the amount and distribution of the compensation.

The DC designs of the Manicouagan system have a much higher unreliability than the AC designs. This is due mainly to the fact that the valves are not overrated so that the loss of a pole represents a loss of transmission capacity. The loss of a pole compares with the loss of an AC line section. In an AC system, however, if a line is lost, the power is automatically transferred to the other parallel lines so there is no loss of transmission and no EPNS penalty.

Isolated DC systems do not have the stability problems of AC systems but additional capacity limitations may nonetheless be necessary to ensure stability of the connecting AC system. This criterion, although not applied to the Manicouagan system designs, can be imposed by TIDE via the maximum allowable power loss per line.

Due to uncertainty in the cost of unserviced load, a graphical sensitivity analysis can aid in determining superior designs as shown in Figure 5.6. For example, design 3 becomes less economical than design 4 when the unreliability cost exceeds half of the generation cost. This observation is explained by the fact that design 3 has only two lines whereas design four has three lines and is therefore less sensitive to line outages. The high unreliability of the DC systems (indicated by the steep slope in Figure 5.6) make these systems more expensive than design 9 (735 kV AC with four lines) when the unreliability costs reach 1.6 times generation costs.

In conclusion, assigning a cost to unreliability (EPNS) provides a correcting factor to the overall cost of the system. The cost of the unmet load ranges from lost revenue of the utility to the societal cost which could be several times higher [15], [77]. It would appear that for the reliability values supplied in the database, DC systems are more sensitive to unreliability than AC systems.

5.7 Addition of Spare Components

In the previous section a cost was assigned to system unreliability to enable more equitable system comparisons, whereas the focus of this section is to use the reliability calculations to further optimize the system design as shown in Figure 5.7. For example, the AC Manicouagan systems designed according to the deterministic N-1 criterion were seen to be very reliable. For instance, as seen in Table 5.10, the most economical design (1) has an EPNS of 5 MW. The N-1 heuristic for the allocation of spares, however, may not necessarily provide the best allocation of resources for each system. Therefore, the more comprehensive design methodology described in section 4.8.5.6 blends the use of both deterministic and probabilistic criteria [47], an example of which is provided below (design 1 of Table 5.8).

The impact of the above-mentioned spare allocation methodology on design 1 of the Manicouagan system is summarized in Table 5.11. The deterministic spare allocation heuristics in this case are: one spare transformer at both sending and receiving ends together with an overrating of the SVC set to 33% (320 MVAr) of the minimum SVC requirements for stability and flat-voltage profile. This table shows the effect on cost and reliability of modifying these basic heuristics by different numbers of spare transformers and SVC blocks (in this example each SVC block corresponds to 480 MVAr) beyond the minimal SVC requirements.

Figure 5.7: Manicouagan Reliability Improvement Through the Addition of Spares.

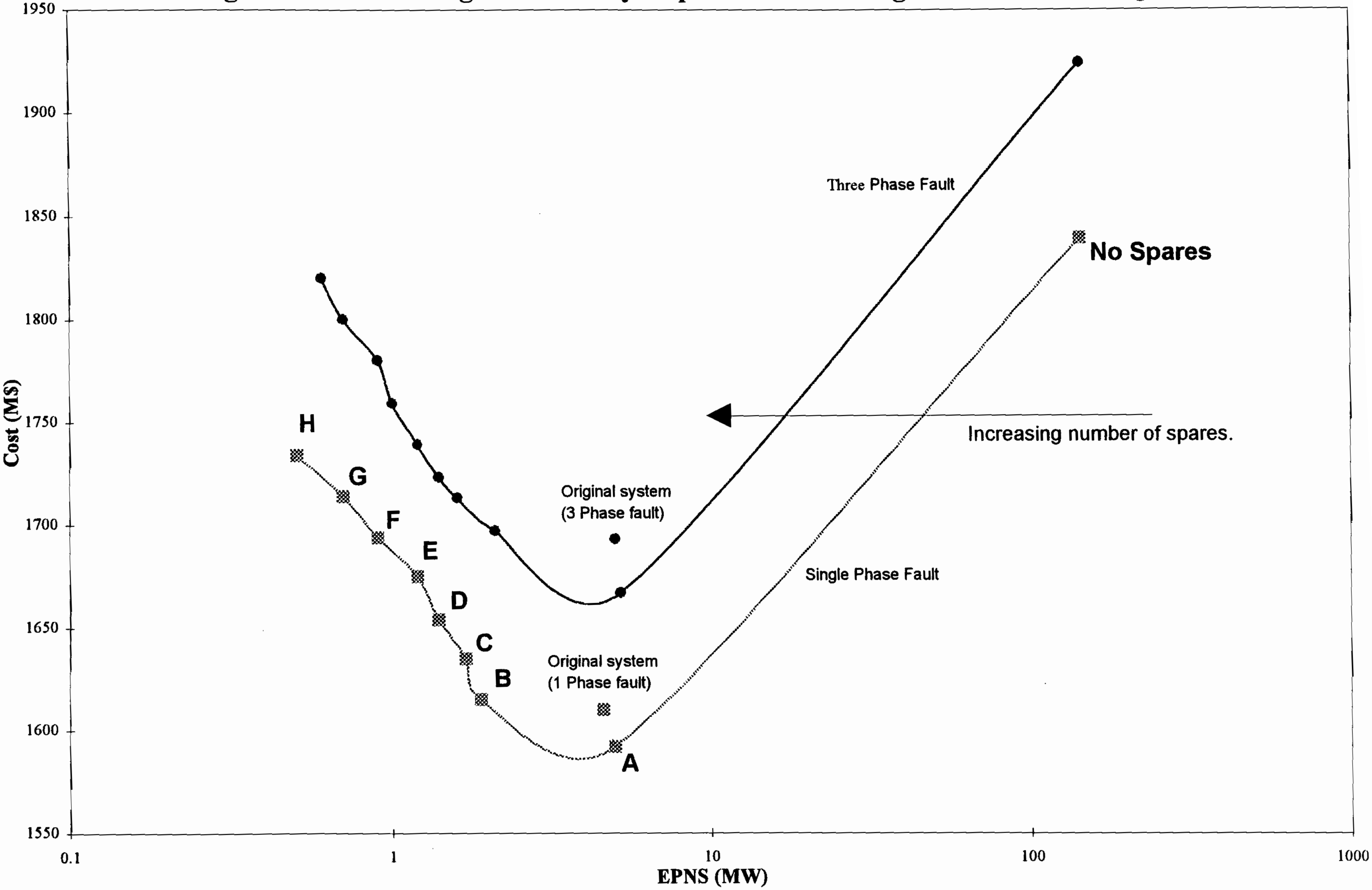


Table 5.11: Addition of Spares to Manicouagan System (Single-Phase Fault).

Design	Addition of Spares		Total Cost	Reliability	
	Transformer	Δ SVC (MVArS)	(incl. spares) (M$)	LOLP (hrs/yr)	EPNS (MW)
Original	+1	+320	1,610	26.8	4.6
No Spares	-	-	1,839	735.	144.
A	+1	-	1,592	28.4	5.0
B	+2	-	1,615	12.4	1.9
C	+2	+480	1,635	11.5	1.7
D	+2	+960	1,654	10.6	1.4
E	+2	+1,440	1,675	9.6	1.2
F	+2	+1,920	1,694	8.6	0.9
G	+2	+2,400	1,714	7.5	0.7
H	+2	+2,880	1,734	6.4	0.5
I	+2	+3,360	1,753	5.2	0.4

Table 5.11 shows that when the spare-allocation heuristics are completely removed (design "No Spares"), the system unreliability increases from the original design values of LOLP= 27 hrs/yr and EPNS= 5 MW to LOLP= 735 hrs/yr and EPNS= 144 MW! This indicates very clearly the great importance of spares in transmission design. The system without any spare transformers or overrating of SVC's is used as a starting point for the addition of spares. Based on the reliability analysis, TIDE determined that the greatest cause of unreliability is due to the transformers since the loss of a single transformer automatically leads to the loss of power transmission capability. The addition of a spare transformer at both ends of the system (design A) significantly improves the system reliability to LOLP= 28.4 hrs/yr and EPNS= 5.0 MW. The 29 M$ capital cost incurred due to the spare transformers is more than compensated with an overall cost savings of 247 M$ from 1,839 M$ to 1,592 M$.

TIDE identified that additional transformers were the next major cause of unreliability (Design B). Despite the 6 M$ decrease in reliability costs, the additional expenditure of 29 M$ is not justified economically and resulted in overall cost increase of 23 M$.

SVC's were identified as the next largest source of unreliability. The addition of a spare SVC block resulted in a further decrease in the unreliability to LOLP= 11.5 hrs/yr and EPNS= 1.7 MW (design C). The extra expenditure of 31 M$ for the SVC block, however, is only compensated by an unreliability cost savings of 1 M$, resulting in an overall cost increase of 20 M$. Thus, for an increase of 480 MVAr in SVC's the cost is not warranted. Thus, consideration should be given to overrating the SVC's rather than adding the user specified SVC block.

The process of adding further spares was continued with the results plotted in Figure 5.7. This figure clearly illustrates that the addition of one transformer, which corresponds to the N-1 criterion, appears to be the best solution from both cost and reliability perspectives. The addition of further spare components is therefore not economically justified for the cost of reliability assumed in TIDE (2,000 $/kW). The overrating of SVC does not appear to be economically justified but other considerations such as maintenance may dictate that some SVC overrating be implemented.

When comparing the original system design with design A it can be seen that the allocation of spare SVC blocks does little to improve the overall system reliability. The inclusion of more SVC's would more likely be included based on operational considerations rather than based on pure economics. The detailed design, however, would provide the data required to have an optimal balance of SVC's and spare transformers.

5.8 General Design Trends

The ability of TIDE to rapidly generate power system designs can be exploited to identify certain general trends in the behaviour of point-to-point transmission systems. One such important trend is the behaviour of the optimum designs over a wide range of transmitted powers and distances for a fixed set of criteria. TIDE has a feature which enables automatic sampling of powers and distances as well as the functionality to graphically display these trends. This global analysis examined 200-300 values of power and distance. For each of these points, as many as 50 designs were considered by TIDE. The data and criteria of Appendix B were used as the basis for these calculations.

The first example (Figure 5.8) shows the least-cost voltage levels for powers up to 26,000 MW and distances up to 1,500 km for a three-phase fault and a maximum of 60% series compensation. It is observed, from this figure, that the power/distance space is subdivided into regions corresponding to the voltage level of the least-cost design. Generally, DC transmission is preferable for long distances and high power levels, a result which is consistent with existing practice [84]. The 735 kV AC voltage has a broad range of operation from about 3 to 12 GW. The 500 kV AC voltage is economical for 1-3 GW and distances below 500 km. The 450 kV DC is more economical for low power levels and distances beyond 500 km as the reliability constraint of at least 2 AC lines increases the cost for long distances and small powers. The power limit separating 735 and 1200 kV depends on the various design criteria but 1200 kV is the preferred voltage level for high power and distances less than 1100 km.

These types of sensitivity tables vary with the criteria used as shown below but maintain a similar pattern. Although it is not possible to generalize on the global trends obtained from such studies, these results would nevertheless be very useful to system planners by offering a broad overview of the various alternatives. These tables also demonstrate that the results provided by TIDE are reasonable.

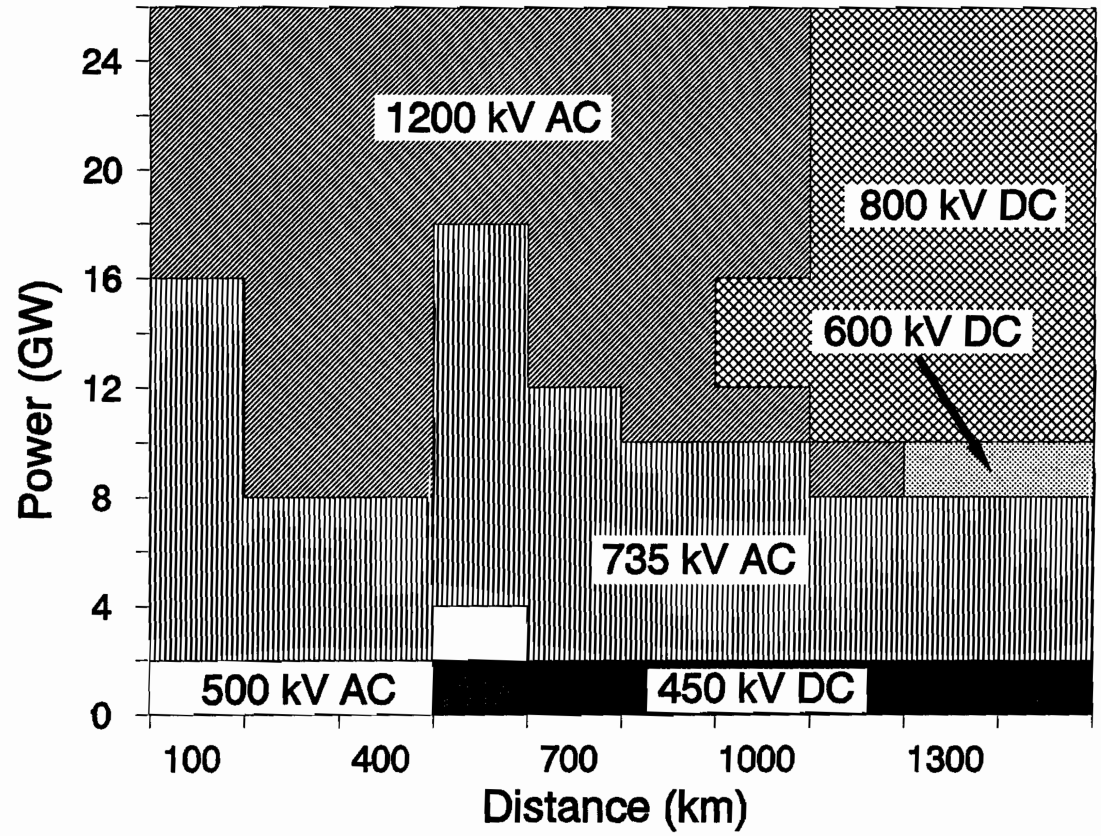


Figure 5.8: Most Economic Voltage: 3ϕ Fault, 60% Maximum Series Capacitance.

The sensitivity of the optimal voltage level to the maximum permissible series compensation and to fault duration was also examined through power/distance diagrams as shown in Figures 5.9 and 5.10. As would be expected, Figures 5.8 and 5.9 show that decreasing the maximum series compensation to 0 reduces the distance up to which AC voltages are economical due to the electrical lengthening of the line.

Figure 5.10 shows the power/distance diagram for a single-phase (compared to a three-phase fault in Figure 5.8) 6-cycle fault with a maximum of 60% series compensation. Comparing Figure 5.8 and Figure 5.10, one can see that the power range of 735 kV AC is reduced for the single-phase fault. This is somewhat surprising but closer examination shows that the expert system is correct. This is because in going from a single to a three-phase fault, the design may call for additional lines. If both voltage levels

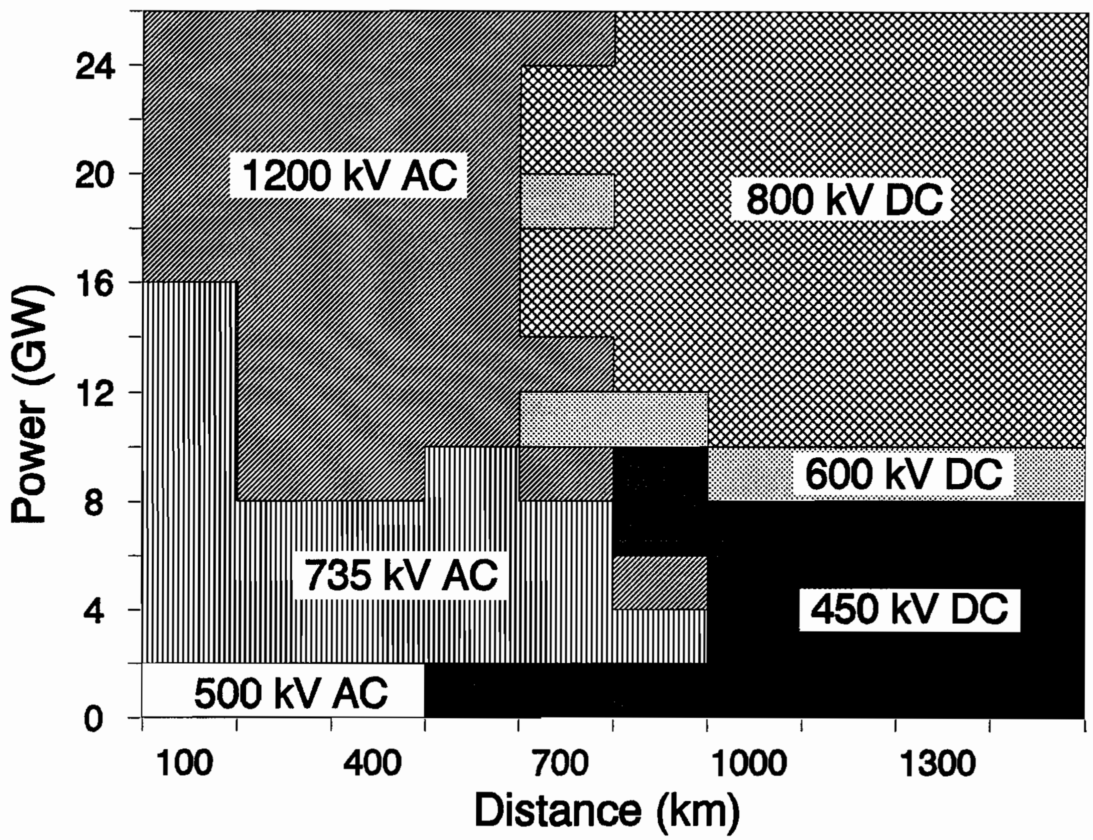


Figure 5.9: Most Economic Voltage: 3ϕ Fault, 0% Maximum Series Capacitance.

required an extra line to meet the three-phase fault, then the 735 kV AC design would be more economical since the unit line costs are much lower than for 1200 kV AC.

TIDE can also demonstrate cost transmission trends for a range of powers and distances. The example shown in Figure 5.11 examines distances ranging from 100 to 2,100 km and powers ranging from 2,000 to 20,000 MW. The AC design criteria used for this example are a three-phase fault and 60% maximum series compensation. When the transmission cost is expressed in $/kW, it can be seen that the normalized design cost approximately increases linearly with distance and is held within a narrow bandwidth ranging between about 100 and 900 $/kW. As the transmission length increases, the cost per kW also grows due to additional losses, compensation, towers and conductors. It can readily be observed that the normalized costs are higher for lower power levels caused by

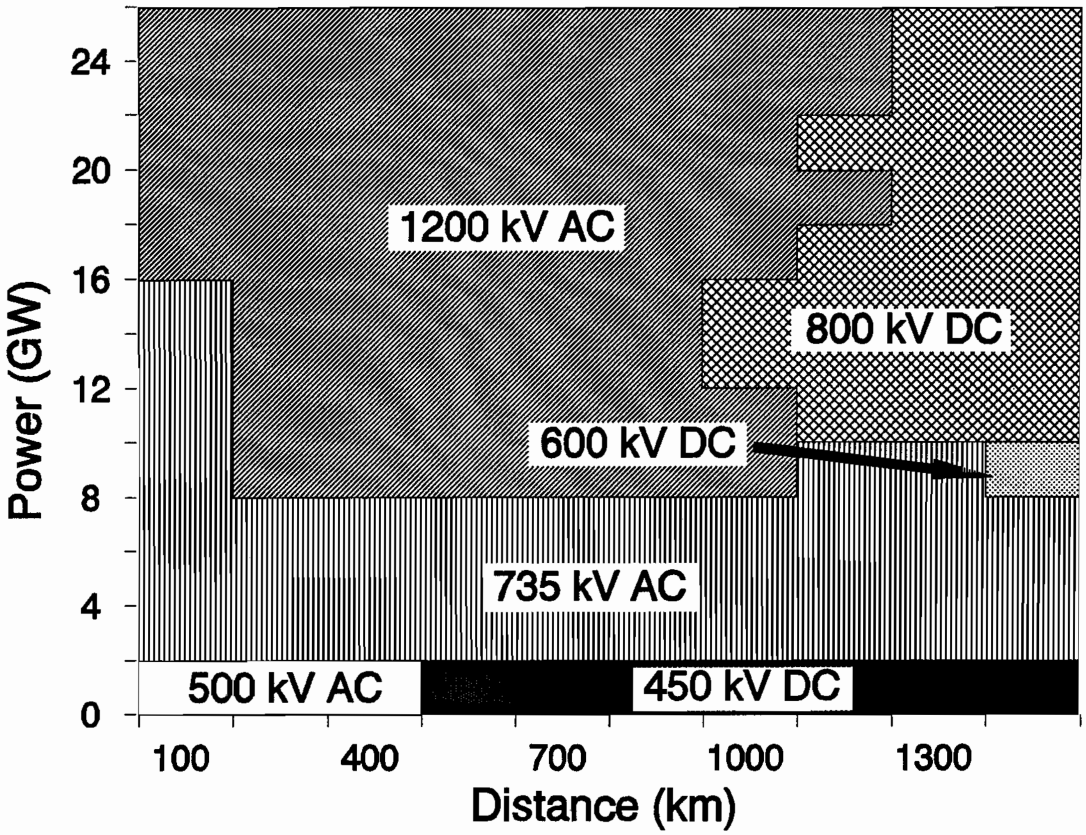


Figure 5.10: Most Economic Voltage: 1ϕ Fault, 60% Maximum Series Capacitance.

the stability and reliability analysis. AC designs are required to have a minimum of two parallel circuits to meet the N-1 design criterion rather than being based on economical constraints. Designs with fewer parallel components are also affected more severely by contingencies.

Interesting trends can also be observed when the transmission design costs are normalized by both the transmitted power and distance. The previous example with cost expressed in $/kW/km is shown in Figure 5.12. Design costs increase for transmission lengths less than 250 km as the fixed component costs, such as transformers, form a much higher percentage of the overall cost than longer transmission lines.

Figure 5.11: Transmission Design Cost as a Function of Power and Distance.

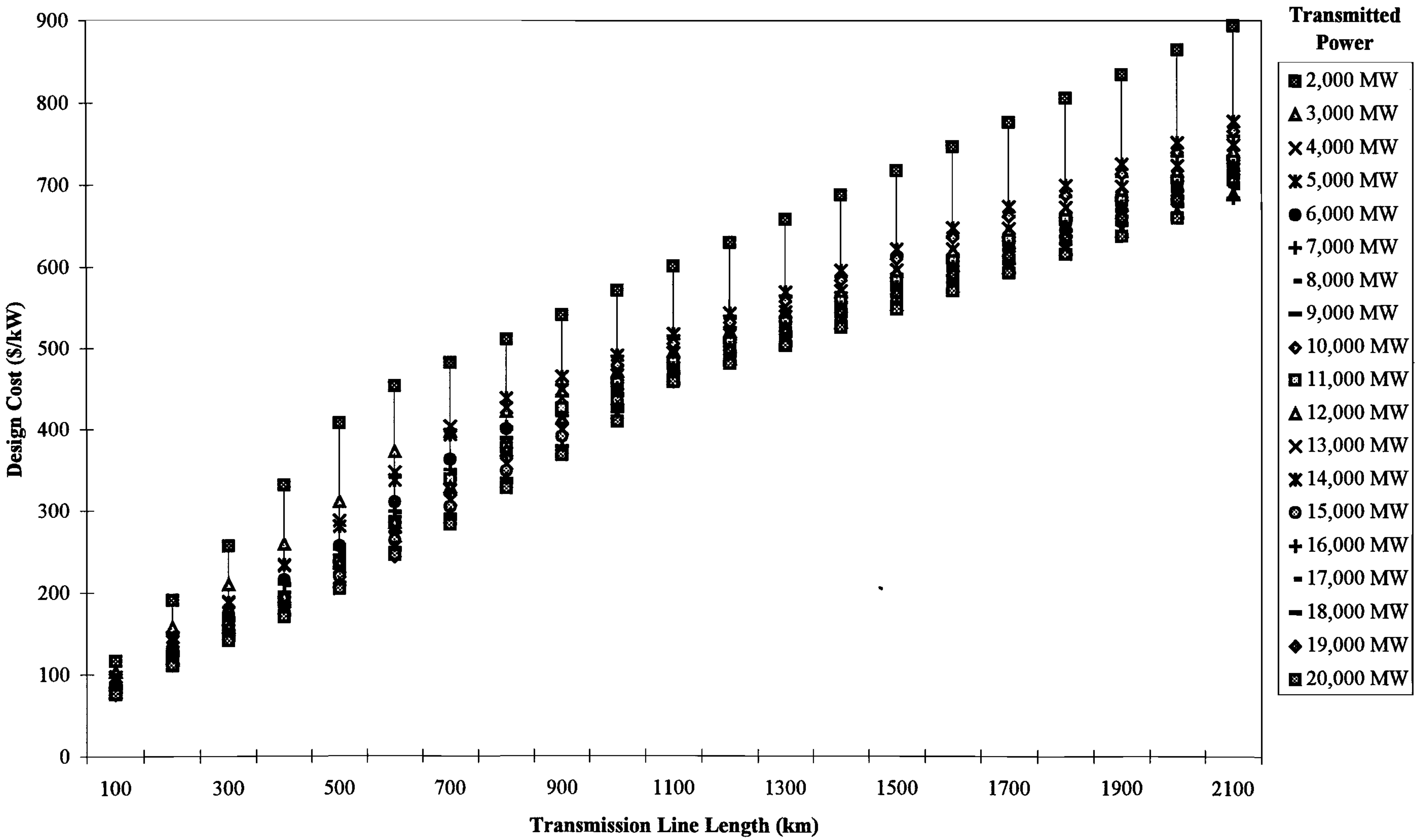
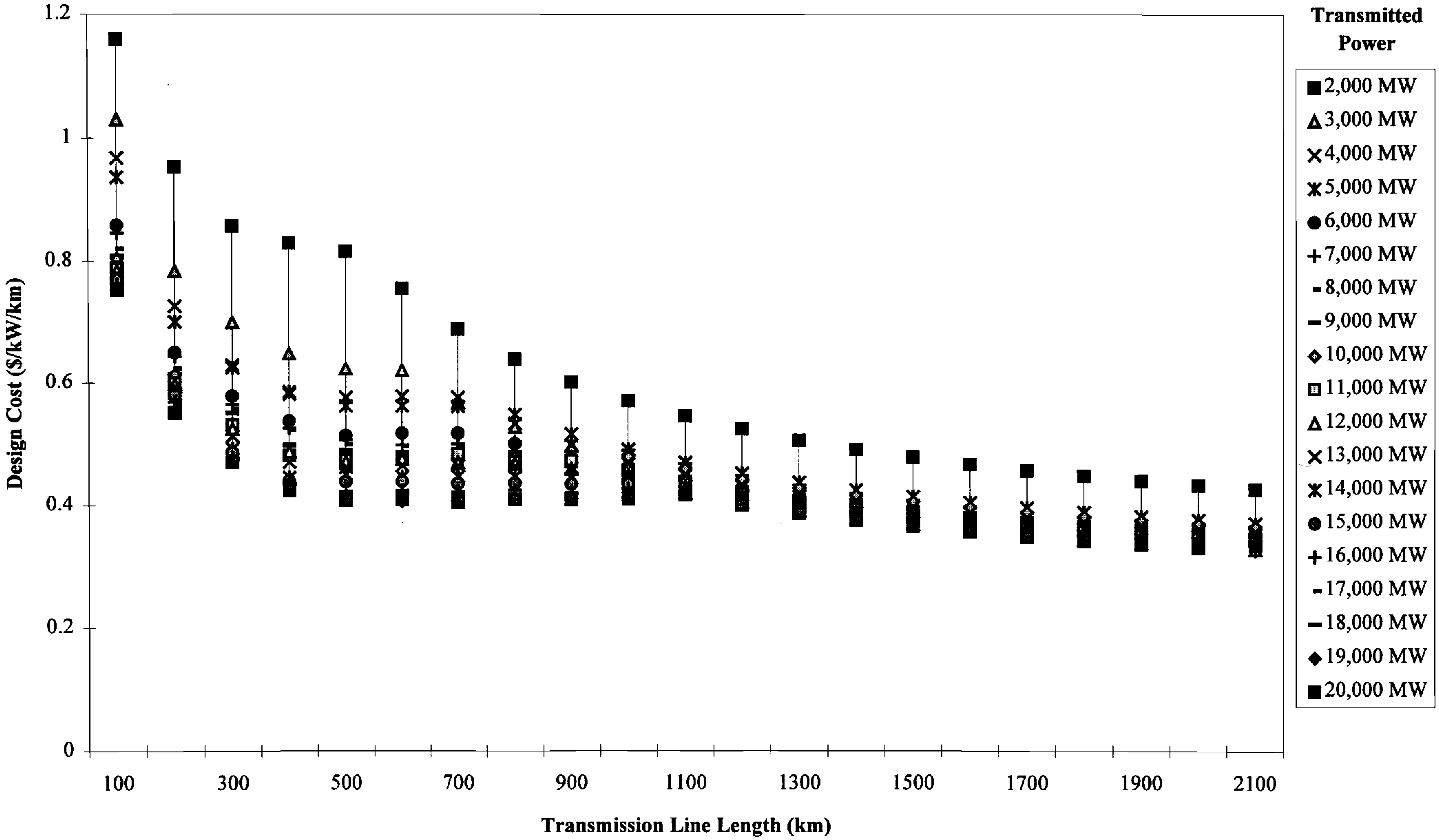


Figure 5.12: Normalized Transmission Design Cost as a Function of Power and Distance.



A breakpoint can be observed in Figure 5.12 for distances around 1,100 km where the normalized cost increases slightly and then decreases. Referring to Figure 5.9, it can be seen for this range of transmission lengths that AC designs are less competitive and DC designs become more economical. This slight increase is due to the changeover of the economical technology. If only AC designs were considered, the costs would increase rather than the observed slight decrease for very long distances.

It is important to observe that, although the design characteristics can change substantially with respect to changes in fault duration (single or three-phase, 6 cycle fault) and maximum series compensation (different voltage levels, different number of lines, compensation, etc.), the unit cost of the design remains relatively insensitive. In some cases, this can be explained by the fact that by meeting the TOV and voltage profile requirements, one automatically satisfies the stability criterion. In other cases, this cost insensitivity can be explained by the fact that there exist enough design degrees of freedom (AC, DC, compensation, lines, substations) to satisfy the requirements without changing the cost substantially.

5.9 Calculation Times

This section discusses the computational time it takes TIDE to design a typical preliminary, point-to-point transmission system. The computer used for these timings was an IBM-compatible PC with a 90 Mhz Pentium and 256 kb of cache memory. Although only 6 Mb of RAM is necessary to execute a typical design session in TIDE, up to 16 Mb of RAM is required when considering sensitivity analyses or general design trends as described in sections 5.3.8 and 5.8. The design times of both the single design sessions and the sensitivity analyses are now discussed.

5.9.1 Single Design Sessions

Typical design times for a single transmission system are shown in Table 5.12 which range from virtually instantaneous results for DC designs to 107 seconds for AC/DC system designs. TIDE's design times depend mainly on the following user specified options: the reliability method, the size of the search space, the search step size of the simulators and the number of components per voltage level.

Table 5.12: Typical Design Times of TIDE.

Designs	Deterministic reliability criterion, Fixed search space	Deterministic reliability criterion, Automatic search	Probabilistic reliability criterion, Fixed search space
AC	15 sec.	21 sec.	105 sec.
DC	1 sec.	1 sec.	2 sec.
AC/DC	16 sec.	22 sec.	107 sec.

Note: These design times are were obtained using the Manicouagan system with a base search space of ±1 circuits, ±1 substations and ±1 voltage levels, one type of equipment per voltage class and using a 5% compensation step size.

The reliability options have the largest effect on the time it takes to design a transmission system. It can be seen in Table 5.12 that the execution times increase by a factor close to seven times for the AC systems when probabilistic reliability calculations are chosen rather than the deterministic N-1 criterion only. The increase in the execution time due to reliability is also dependent on the number of components considered in the reliability calculations as well as the number of states to be analyzed. Therefore the AC systems will be much more affected than the DC systems, as they have considerably more of types of components. The reliability execution times provided in Table 5.12 consider 5 components with 122 states for each AC design and a single equivalent line-terminal component with 5 states for the DC systems.

The size of the search space determines the number of designs considered in TIDE and thus affects the design time. There are two search-size examples shown in Table 5.12, a fixed search space and an automatic search space. The fixed search space used in this example is defined by an AC range of ±1 circuits, ±1 substations and ±1 voltage levels and a DC range of ±1 voltage levels all with respect to the expert system base values. This will yield up to 27 optimized AC systems (3 circuits * 3 substations * 3 voltage levels) and 3 DC systems assuming that there is a single component per voltage level. The automatic search space, controlled by the Search strategy module, considers at least as many designs and is dependent on the expert system module's initial estimate.

The search step size controls the accuracy of the AC compensation which must be added to meet the design criterion. In Table 5.12 the step size used in TIDE was set at 5%. The design engineer can modify this value but with all the other inherent approximations in the preliminary designs process, more accurate results are not usually warranted. Larger step size will tend to make the results more conservative. Small compensation step sizes can significantly increase TIDE's execution times.

TIDE's design process always considers all combinations of all possible components for each voltage level present in its database. Thus, if many different components are available, the execution times may rise significantly. For preliminary design, however, this is not a problem as usually only representative components are entered for the screening process and specific component models are considered with a reduced search space or in the detailed design. For the designs considered in this chapter, the number of transmission line conductors considered were four for AC systems and three to six for DC systems. Thus the execution times for an AC/DC system would be in the order four times those of Table 5.12.

5.9.2 Sensitivity Analysis

When general sensitivity analyses are performed, the design times are significantly higher as hundreds of single designs are performed for each analysis. For instance, the time to perform the calculations of a power-distance graph, as seen in Figure 5.10, takes about 10 hours. This search consisted of 300 power/distance design points and their corresponding AC/DC systems designs including reliability calculations. Only one component was considered for each voltage level to limit the overall execution time. For each design point 10 least cost designs were saved. Thus, results of about 9000 designs were retained occupying in the order of 1.8 Mb of disk space. TIDE provides a graphical or tabular interface to analyze these results from various points of view.

5.9.3 Summary

The calculation times to execute TIDE vary in the order of; 10 to 20 seconds for a simple AC/DC design case, of the order of 100 seconds including probability analysis and of the order of 10 hours for a two dimensional sensitivity analysis. The response time for single designs is sufficiently rapid that it encourages the design engineer to test a variety of designs and criteria which would not otherwise be possible. Two dimensional sensitivity analysis is still a very lengthy process. However, when considering the magnitude and complexity of the design analysis involved, it would be beyond the scope of any other tool using detailed analysis, and is still performed within a reasonable amount of time.

5.10 Summary

It can be seen from this chapter that TIDE is a design environment which is versatile, comprehensive and intelligent. TIDE enables transmission designs to be analyzed with respect to the type of transmission (AC or DC), voltage levels, number of circuits and substations, compensation levels, cost and system performance. This analysis permits designs to be compared and the strengths and weakness of each identified. To further ensure the robustness of the system designs, sensitivity analyses to system parameters and design criteria are readily performed. Examples of sensitivity analysis of fault type, design flexibility and changes in costs were shown.

TIDE's design environment was validated not only by cross-comparing various recommended design alternatives but also with existing transmission systems. The system designs obtained by TIDE compared favourably with existing system designs in the scope of preliminary transmission planning.

The reliability of transmission-system designs were computed and costed. Reliability is used in TIDE as an aide to enable further comparison of prospective designs and as well as to enable sensitivity studies on the cost of unreliability. Reliability was also used to allocate the optimal number of spare components in a design.

Finally, the design scope was broadened to include general transmission trends which demonstrated optimal voltage levels for a wide range of powers and distances and their sensitivity to various design criteria. Transmission cost trends were also investigated.

Thus, TIDE has been shown to be able to design a wide range of transmission systems and compare designs from many different perspectives. General transmission design knowledge can be extracted from the results generated by TIDE to further a design engineer's understanding.

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

The main objective of this thesis was to develop and test an intelligent tool to automate the preliminary design process of AC/DC, point-to-point transmission systems integrating the principal knowledge and analysis tools available. The goals were to identify, model and preserve expert preliminary transmission design and analysis knowledge in a user-friendly environment, to integrate the appropriate planning tools and to automate the design process. This was achieved by developing an intelligent design environment called TIDE (Transmission Intelligent Design Environment).

When knowledge is represented in an efficient, well-structured manner and is harmoniously managed, it becomes possible to mirror an engineer's design methodology. To accomplish this goal, TIDE structures design knowledge according to three main categories of knowledge representation: object databases, expert systems, and simulators.

The object-database contains data about equipment, design expertise, design criteria, transmission systems, and housekeeping. The expert system component of TIDE is essentially the nerve centre which processes knowledge from both the object-data base and the simulators as well as controlling the overall reasoning. Several expert system modules were developed to carry out these tasks namely, the creation of a set of design skeletons, simulator control, costing of designs, search strategies, menu control and data base validation. Finally, TIDE integrates a number of numerical simulators for voltage control as well as AC load flow, transient stability and reliability analyses. TIDE is implemented on a PC platform using the expert system shell NEXPERT [5] for expert system and database components, and QUICKBASIC [4] for the numerical simulation modules.

TIDE is fast and efficient, being able to generate a large number of realistic designs meeting all the specifications in a matter of seconds. Its holistic design approach results in flexible, simple and reliable systems. Each is designed to meet a number of design criteria. For AC systems these are: maximum temporary overvoltage, flat-voltage profile for heavy and light loads, AC load flow feasibility, transient stability and reliability (adequacy and security). For DC systems the criteria are: maximum line regulation, maximum power loss due to the outage of one pole and system reliability. TIDE considers both types (AC or DC) of transmission, as well as various voltage levels, topologies and compensation types and amounts.

TIDE was validated by comparing various existing power systems (Manicouagan, James Bay, Peace River and Nelson River) with those proposed by TIDE for the same basic input specifications. An in-depth comparative analysis was also carried out for the Manicouagan system. The characteristics of this system design and its sensitivity to fault types, expandability and cost were discussed in great detail. TIDE was shown to generate comparable preliminary designs to those systems already in existence as well as providing extensive relevant information (such as cost, performance, reliability and parameter sensitivity) in selecting the best design.

TIDE has the option of carrying out an elaborate reliability analysis during each design session. State enumeration was used for the reliability calculations. TIDE's reliability results can focus on individual states or on system-wide measures such as LOLP or EPNS. Analysis of individual states can pinpoint specific system problems and give an indication as to the types of expected system failures. Various graphical methods were developed to aid in interpreting the overall system reliability indices. Cost penalties were also added to the overall transmission costs to provide a way to quantify system unreliability and thereby permit the comparison of systems according to both cost and reliability. Reliability was also used to identify system weaknesses. In such cases, TIDE adds spare transformers and static VAr compensators to meet a minimum desired system reliability level. Finally, it was observed that the N-1 design criterion results in very reliable AC system designs, although DC systems tended to be much more unreliable based on the standard published failure data used in this thesis. Thus, the results obtained through TIDE suggest that reliability is particularly important when comparing AC and DC systems.

TIDE can also be used to produce general transmission trends by automatically determining appropriate voltages for a large spectrum of the design parameters power and length. These trends change somewhat with respect to the maximum series compensation levels and stability criterion but the cost per kW for the least-cost design is relatively invariant. It was also observed that the optimum design transmission costs per kW increase almost linearly with distance. As would be expected, increasing the AC fault duration and decreasing the maximum series compensation tends to makes the DC systems more attractive.

In conclusion, TIDE is a powerful and easy to use tool for the preliminary design of point-to-point transmission networks integrating a number of diverse design activities and data. TIDE has been shown through extensive tests and comparisons with existing networks to be able to emulate the designs of human experts. Its automated features are capable of examining hundreds of potential designs and of recommending realistic solutions from the points of view of cost and reliability in a matter of seconds. In addition, TIDE can generate sensitivity and comparative studies with respect to several design parameters, a useful step in the choice of the final design.

6.2 Claim of Originality

The originality of this thesis lies in the integration of the individual modules constituting TIDE and in the resulting synergy of the design environment. To the best of this author's knowledge the following are considered as original contributions of this thesis:

1) An *intelligent design environment (TIDE)* was developed for the preliminary design of AC/DC point-to-point transmission systems integrating a multiplicity of cooperating expert system modules, databases and simulation tools including AC load flow, voltage control, stability, reliability and costing. Transmission systems were conceived using design rules in a manner similar to design engineers and thus encompassed the main practices, criteria and procedures used by human experts in power transmission design.

2) The developed environment TIDE *structures and preserves* AC/DC transmission design knowledge which is widely dispersed and subject to erosion due to retirements and insufficient replacement of human experts.

3) TIDE was *extensively tested and validated* on existing power networks.

4) TIDE has been shown to be a *powerful tool* for the preliminary design of power networks for experienced engineers as well as a training tool to help understand the design methodology. The main original features of TIDE are:

    a) The design knowledge and other parameters can be easily *altered* according to various design situations.

b) TIDE integrates *cost and reliability* calculations for both AC and DC systems. Both *adequacy and security* are considered for AC systems which are also analyzed using AC load flow and stability.

c) Systems can be designed to *meet a given probabilistic reliability criterion* through the addition of spares rather than solely based on deterministic criteria such as N-1.

d) *Generalized transmission planning results* such as power-distance tables and parameter sensitivity analysis results can readily be generated.

5) TIDE's design environment has helped *bridge the gap between preliminary and detailed transmission design* by providing realistic design alternatives which can be studied and compared in a short period of time. This tool enables faster, more comprehensive preliminary design which will result in a shorter detailed design process and superior designs.

6.3 Recommendations for Future Research

Three areas have been identified for possible future research activities. One is the development of a more general intelligent planning and design environment beyond point-to-point power transmission. Alternative areas of future research include the addition of new functionality to TIDE and improving TIDE's modelling accuracy.

A General Intelligent Planning and Design Environment:

As additional features and capabilities are being added to TIDE, it is emerging as one member of a set of satellite expert systems covering the whole gamut of power system planning. TIDE and the satellite expert systems are foreseen to form the basis of a global approach to the planning and design of power systems which will encompass all major system enhancements. These satellites will include insulation coordination [42] as well as the design of components such as transmission towers [87], substations [9] and interconnections [26]. The insulation coordination and transmission tower design modules can be used to supply line data for TIDE. The substation module can either provide more accurate costs of the substation equipment for TIDE or be used to perform detailed design of the suggested systems. The interconnection design module is foreseen to use the results generated by TIDE to design tie lines between interconnected regions.

New functionality:

Using the basic tools provided in TIDE there are many readily-implementable enhancements that would provide additional information to the system planner. The sensitivity analysis of any design parameter is possible but must be selected and performed manually. To aid the planner in interpreting the design results and help select the best system design, an expert system is envisaged identifying system weaknesses, performing sensitivity analysis on critical parameters and recommending further studies.

Additional information in selecting the best scenario could also be provided by ranking systems based on a list of what-if scenarios determining the required flexibility or sensitivity for that specific system. For example, determining the cost of upgrading the stability design criterion from a single-phase fault to a three-phase fault could be automatically calculated.

A supervisory expert system could be foreseen to guide the system planner in the usage of TIDE by providing hints and suggestions regarding the reasonableness of design criteria relative to the typical standards, design expertise, and values entered in the equipment database. This supervisory expert system would operate in a manner similar to a planning expert looking over the shoulder of a junior engineer to avoid unrealistic scenarios and warn of unusual combinations of data.

TIDE is presently a design tool and does not explicitly consider staged transmission installation sequences or the variable costs of system operation. Time aspects of money such as accrued variable costs, equipment economic life (and their replacement), inflation, interest during construction, project financing, depreciation, as well as the ability of a utility to raise capital were not explicitly considered as they were anticipated to be included in the input capital cost of the equipment [104]. Overall optimization over a planning horizon could also be envisaged.

Additional functionality such as environmental impact and right-of-ways can also be foreseen. In addition, different knowledge bases could be developed accounting for varying socio-economic environments and criteria.

One of the main objectives of this research was to bring preliminary and detailed transmission planning closer together. Once a best design has been decided in TIDE then detailed studies must follow. A load flow data-bridge has already been written to translate TIDE's load flow data to CYME's load flow [1] data format. Additional data bridges to other detailed design simulation packages could be provided, to further reduce the transition from preliminary to detailed transmission design. It is envisaged that TIDE could exploit this data bridge to perform more accurate detailed system studies for the final set of potential designs.

The person-machine interface could be extended and modernized considerably. Exploiting the speed of TIDE's expert systems and simulators, a training tool can be envisioned where a specific transmission network is represented graphically and its parameters modified so that the resulting effect on the system would be immediately observable. In addition, other modern features of intelligent system modelling such as a purely object-oriented could be used to enhance the flexibility and expandability of TIDE.

Improve Modelling Accuracy:

The stability models of TIDE could be improved in both accuracy and detail. Stability could be based on pure simulations or through enhanced direct methods. Transmission line losses and overvoltage modelling could be improved by adding the effect of corona.

The reliability module could be enhanced to consider double contingencies, sympathetic outages as well as a more detailed component model. An expert system could also aid in reducing the reliability computational burden by further prioritizing the contingencies to be examined. Separate corridors could be considered for reliability calculations.

A learning module can be foreseen to extract design experience from the preliminary transmission designs generated by TIDE to enhance the knowledge base. If this knowledge base is inaccurate, a much larger time-consuming search space is required to ensure optimality. Paralleling the training process of an apprentice, TIDE could use the least cost transmission designs to modify the design knowledge base thus improving the expert system's initial estimate.

6.4 Final Thoughts

When discussing a branch of computer science that identifies itself as artificial intelligence (AI), it is important to understand what is meant by intelligence and how readily it is modelled when developing an application. The following section describes the author's impressions of understanding intelligence and obtaining knowledge when developing an expert system.

A distinction is being made between *strong AI,* which refers to having the full ability of humans to reason, think and be creative, and *weak AI* which deals more with simulating human activities to reason rather than having the full human potential. The notions of what constitutes intelligence will continue to evolve as tools mature and experience is gained through the development and use of AI systems. Expert systems (ES), as used in this research, would be classified as weak AI.

Attaining even *weak* levels of AI requires tremendous knowledge acquisition, classification, structuring and coding. This is somewhat less surprising when one considers the level of knowledge of the design engineer from whom this knowledge is being extracted. A design engineer's education will include at least 15 years of schooling and another 10 to 20 years practical experience in industry. With the ES tools presently available, one cannot hope to encapsulate this magnitude of knowledge and reasoning ability in the few years devoted to develop such a tool. Developing an ES tool not only involves identifying domain knowledge but also structuring and coding the knowledge in an efficient way to be understood by the engineer and reasoned upon by the ES tool. This effort explains why most engineering ES system development is restricted to a narrow topic.

The knowledge engineer is presented with many problems when acquiring the domain knowledge necessary for the intelligent system. Although knowledge often may be gleaned from published documents, one of the best sources are domain experts. In the development of TIDE, it was observed that design engineers thought more in terms of examples and specific cases rather than in generalized methodology or design rules. This is to be expected as an expert's training is not to enumerate all possible knowledge but to focus on and use what is relevant for a specific task or situation.

When developing an intelligent system, knowledge must be extracted and compiled into an appropriate knowledge format. The best way to translate this knowledge is often not clear and only develops into a well structured, efficient format through many attempts and using previous experience. This is partially due to the various sources of knowledge as well as the less than intuitive methods typically used in ES to represent knowledge.

ES must continue to grow and expand to handle ever larger real-world problems. When considering such a projet, the effort required to encapsulate, structure, understand and process knowledge should not be underestimated. One of the most difficult types of knowledge to attempt to encapsulate is an expert's intuition of sensing that designs don't look right and his/her ability to draw on their experience to solve the problem at hand. Experts frequently rely on their intuition, which is not readily quantifiable. Obtaining and representing design knowledge tends to be an iterative process whereby knowledge is gained from various sources such as experts and available literature, implemented in the AI environment and then tested. Through subsequent tests, missing knowledge and the scope of the existing knowledge are identified.

Although an expert system, such as TIDE, is not powerful enough to replace a design engineer, it provides consistent results, is not swayed by feelings, lack of sleep and emotions. It does not feel the pressure to get the task accomplished and thus takes the necessary time to search a broad enough scope to ensure the preliminary design is covered. It also ensures a breadth of designs which might be overlooked. The predictability of the knowledge entered into TIDE is what makes it surprising that experts are indeed able to learn from such systems. In the experience with TIDE, useful trends were identified and designs which seemed counter-intuitive were in fact correct. Our experts were able to realize more fully the effects of their design knowledge and be challenged by inconsistent preconceptions.

Intelligence, in this restricted context, lies in the ability to simulate human activities, by providing basic reasoning skills, to skillfully integrate various design tools and most importantly to explain why choices and decisions were made. As TIDE was created for engineers, confidence in the results of this tool will only come through reasonable results and the ability to answer the question "why" when discrepancies arise.

Although TIDE has come a long way in understanding the design process of a point-to-point transmission system, it still has much to learn. It cannot remain static but must grow, expand and continue its quest for deepening knowledge and intelligence. I wish it well for it still has much to learn about the real world.

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APPENDIX A.
USER INTERFACE MENUS

A.1 Introduction

A user-friendly menu-based interface has been developed for TIDE. This appendix provides an overview of its principal menus and options. Dynamically updated menus and context-sensitive help assist the system planner to enter the required data and to examine the design results in a variety of forms (graphs and tables). Explanations are also provided during the design process to facilitate comprehension of the design methodology. The complete input data requirements for TIDE can be seen in Appendix B while Chapter 5 summarizes the main output tables.

TITLE MENU:

The title menu, Figure A.1, lists the main contributors of TIDE version 1.0.

```
              TRANSMISSION INTELLIGENT DESIGN ENVIRONMENT

                           T I D E                    V. 1.0, 1995

                    An Expert System For The Preliminary
              Design Of High Voltage AC/DC Power Networks

   DOMAIN ENGINEER:             Mr. D. McGillis, Hydro-Québec

   KNOWLEDGE ENGINEERS:         Mr. L. Loud, McGill University
                                Dr. F. D. Galiana, McGill University

                    HIT ENTER TO START EXPERT SYSTEM
```

Figure A.1: Title Screen.

The next screen, Figure A.2, is the main menu which provides access to the principal components of the planning environment including databases, expert systems for transmission design, performance summary and evaluation, and sensitivity studies. A sample case, detailed in Chapter 5, has been loaded and will be used in the following example. Each of the main menu items will be discussed in turn.

```
FILE:MANQC1RA      DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                        M A I N   T I D E   M E N U

     HELP                                  DATA BASE MANAGEMENT
     DESIGN SPECIFICATIONS                 PRINT
     EQUIPMENT DATA BASE                   SENSITIVITY STUDIES
     EXPERT SYSTEM EXECUTION               SETUP or LANGUAGE
     PERFORMANCE                           GO TO DOS
     USER DESIGN
     DELETE DESIGNS

   DESCRIPTION OF FILE l:\transept.ful\session\MANQC1RA
   Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                                GET GENERAL HELP ABOUT TIDE.
```

Figure A.2: Main Menu.

HELP MENU:

The help menu provides general help in navigating the various menus of TIDE. Help lines for individual menu items are shown at the bottom of each screen depending on the cursor location.

DESIGN SPECIFICATIONS:

Figure A.3 contains the design parameters common to the AC and DC systems as well as providing access to AC and DC design specification submenus. The common design specifications are power, distance and cost of generation.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                     DESIGN SPECIFICATION SELECTION MENU

      INPUT PARAMETERS                       SELECTION MENU

MAXIMUM POWER GENERATED (MW) : 5000
                                         AC DESIGN SPECIFICATIONS
LINE LENGTH (km) : 600.0

COST OF GENERATION ($/kW): 2000          DC DESIGN SPECIFICATIONS

YEAR OF COST: 1991

REFERENCE: Hydro-Québec
                                                                RETURN

                         ENTER MAXIMUM REAL POWER GENERATED IN MW.
```

Figure A.3: Design Specifications Menu.

The **AC design specifications** outlined in Figure A.4 are subdivided into design parameters and control parameters. The AC design parameters consist of the nominal voltages and TOV_{MAX}, reliability and stability criteria, as well as the system frequency.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                         AC DESIGN SPECIFICATIONS

     DESIGN PARAMETERS                   CONTROL PARAMETERS

NOMINAL VOLTAGES AND TOVMAX        ALTERNATIVE DESIGNS AND SIMULATION CONTROL

RELIABILITY                        VOLTAGE AND SUBSTATION RULES

STABILITY                          COMPENSATION STEP SIZE

SYSTEM FREQUENCY

                                                                RETURN

  ADD, MODIFY OR EXAMINE NOMINAL VOLTAGES AND MAXIMUM TEMPORARY OVERVOLTAGES.
```

Figure A.4: AC Design Specifications.

An example of an AC stability criteria menu is shown in Figure A.5. These specify a number of parameters such as fault type and duration, and number of lines lost as well as a number of limits on design parameters affecting stability.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                         AC STABILITY CRITERIA

                                              *
        TYPE OF FAULT :  SINGLE-PHASE
                                            *
        FAULT DURATION (CYCLES): 6
                                            *
        LINES OUT BEFORE FAULT : 0
                                            *
        LINES OUT AFTER FAULT : 1

        SCMAX {O =< VALUE =<95%}:  60.0  %

        DMAX : 40  degrees       SVC RATING - SVC'S ONLY

        SVCMAX :     50.0 %      SVCMIN :    -30.0 % (of maximum power)

        STAB V MAX :  1.1 p.u.   STAB V MIN :  0.6 p.u.

               * PRESS F2 TO GET A MENU.                    RETURN
     PRESS F2 TO SELECT EITHER SINGLE-PHASE FAULT OR THREE-PHASE FAULT.
```

Figure A.5: AC Stability Criteria.

AC control parameters, also accessible through the AC design specifications menu, contain design data used by the design expert system to formulate preliminary systems. An example of a control parameter menu is shown in Figure A.6 in which the type and bounds of the search strategy are specified. Search ranges are defined for the number of circuits, substations and voltage levels. Flags can also be set to enable graphical output of the series and shunt compensation adjustments while meeting TOV and stability criteria.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                 ALTERNATIVE DESIGNS AND SIMULATION CONTROL MENU

 Alternative Designs
 Alternative           |Number of     |Number of
                       |Circuits      |Substations
 ---------------------------------------------------
 Base Voltage          |1             |1
 Voltage Sensitivity   |1             |1              VOLTAGE SEARCH RANGE
                                                              1

 Simulator control
 Optimize for...   |? *
                   |
 ------------------------
 Stab Plot         |False
 TOV plot          |False                    * CUBIC SEARCH

                                     * PRESS F2 TO GET A MENU.     RETURN

                                        SELECT THE SEARCH SPACE.
```

Figure A.6: Search Space Control.

The **DC design specifications**, Figure A.7, define the DC reliability criteria as well as the design expertise required to formulate preliminary system designs. An example of the DC specifications are the available voltages and the voltage search range shown in Figure A.8.

EQUIPMENT SPECIFICATIONS MENUS:

The **AC equipment specifications** menu shown in Figure A.9 provides access to the AC equipment database. Data for each AC component is accessed through a separate menu. Similarly, DC equipment is accessed through the **DC equipment specifications** menu shown in Figure A.10. An example of an equipment menu is shown in Figure A.11 for AC lines. Line characteristics are specified for each AC line type including rated voltage, power rating, impedances, reliability data, line availability as well as identification codes.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

DC DESIGN SPECIFICATIONS

MAXIMUM POWER LOSS CRITERION

DC VOLTAGE RULES

DC NOMINAL VOLTAGES

RETURN

MODIFY OR EXAMINE DC MAXIMUM POWER LOSS CRITERION.

Figure A.7: DC Design Specifications.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

DC NOMINAL VOLTAGES

Voltage Name	V Rated kV	Voltage Availability*
v_dc1	250	True
v_dc2	450	True
v_dc3	600	True
v_dc4	800	True

VOLTAGE SEARCH RANGE 1

Add / Delete Voltages

* PRESS F2 TO GET A MENU

RETURN

MODIFY OR EXAMINE DC NOMINAL VOLTAGES.

Figure A.8: DC Nominal Voltages.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                  AC EQUIPMENT SPECIFICATIONS MENU

                    GENERATION
                    LINES
                    LOAD
                    SERIES CAPACITORS
                    SHUNT INDUCTORS
                    STATIC VAr COMPENSATION
                    SUBSTATIONS
                    TRANSFORMERS
                                                          RETURN

                        MODIFY OR EXAMINE GENERATOR DATA.
```

Figure A.9: AC Equipment Menu.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                  DC EQUIPMENT SPECIFICATIONS MENU

                  TERMINAL STATIONS
                  BIPOLAR LINES

                                                          RETURN

                     ADD, MODIFY OR EXAMINE TERMINAL DATA.
```

Figure A.10: DC Equipment Specifications.

EXPERT SYSTEM EXECUTION MENU:

The expert system execution menu, Figure A.12, starts the AC and/or DC design process. Explanation levels are set in this menu depending on the desired level of detail.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

AC LINE SPECIFICATIONS MENU

TYPE OF LINE DATA

Line Name	V Rated* kV	Power Rating MVA	B μS/km	R mΩ/km	X mΩ/km	Failure Freq. /yr /100km
L3151	315	870.0	4.26	48.3	370.65	0.2988
L3152	315	1360.0	4.26	23.8	370.65	0.2988
L3153	315	1160.0	4.26	31.6	370.65	0.2988
L3154	315	980.0	4.26	40.6	370.65	0.2988
L5001	500	2770.0	4.64	24.2	340.3	0.4038
L5002	500	4330.0	4.64	11.9	340.3	0.4038

Add / Delete Lines
Modify line_ac's Properties

* PRESS F2 TO GET A MENU

RETURN

MODIFY OR EXAMINE DEFAULT LINE DATA.

Figure A.11: Sample Equipment Specifications.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

EXPERT SYSTEM EXECUTION MENU

AC/DC DESIGN EXECUTION

AC DESIGN EXECUTION

DC DESIGN EXECUTION

SET EXPLANATION LEVEL

RETURN

RUN BOTH AC AND DC EXPERT SYSTEMS.

Figure A.12: Execution of Expert System Menu.

SIMULATOR OUTPUT:

The simulator provides graphical output of the design process, reliability analysis and a topological summary of the various designs. An example for the Manicouagan system is shown in Figure A.13.

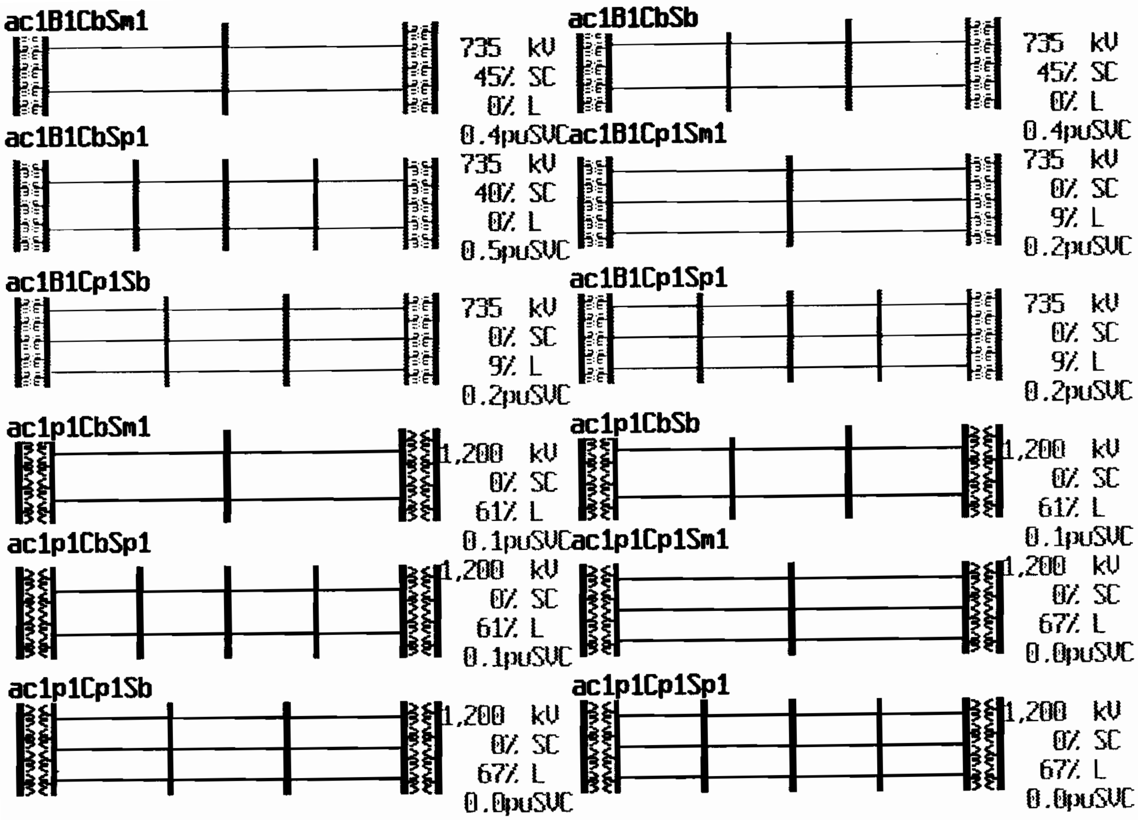


Figure A.13: Sample Simulator Output.

PERFORMANCE MENU:

The performance menu, Figure A.14, provides access to summary menus of the results of the optimized preliminary transmission system designs. AC and DC system performance may be analyzed separately or together and may be sorted by the various output criteria. An example the output results is shown in Figure A.15. The sort criteria is the class property 'transmission cost including unreliability'. Sensitivity to various costs can also be determined and is summarized in Figure A.16 and is either shown in tables or graphs.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

PERFORMANCE MENU

AC/DC PERFORMANCE

AC PERFORMANCE

DC PERFORMANCE

SORT CRITERIA

RETURN

EXAMINE THE COMBINED AC AND DC DESIGN SUMMARY.

Figure A.14: Performance Menu Options.

FILE:MANQC1RA DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

GENERATED POWER(MW):5000 LINE LENGTH(km): 600.0

AC/DC DESIGN SUMMARY

C_TRANSM_W_unReliability

Design Name	V Rated kV	Total w/rel (M$)	Total Cost (M$)	Equip Cost (M$)	Cost Loss (M$)	EPNS M$	LOLP hrs/yr	EPNS MW	No. of Line	L C (
ac1p1Cp1Sm	735	1633.	1629.	1411	218	4	15.13	2.2	3	1
ac1p1Cp1Sb	735	1682.	1681.	1463	218	1	10.15	0.7	3	1
ac1p1Cp1Sp	735	1733.	1733.	1515	218	0	3.46	0.2	3	1
ac1p1CbSm1	735	1743.	1724.	1396	328	19	18.27	9.7	2	7
ac1p1CbSb_	735	1783.	1754.	1428	326	29	26.61	14.5	2	7
ac1p1CbSp1	735	1801.	1763.	1437	326	38	34.83	19.2	2	7
dcL6001ter	600	1930.	1806.	1438	368	124	408.96	62.4	2	5
dcL4505ter	450	1976.	1840.	1302	538	136	444.39	68.2	2	5
a31p1CbSb_	735	2021.	2021.	1857	164	0	1.43	0.1	4	1
a13B1CbSb_	500	2077.	2076.	1616	460	1	13.53	0.8	4	1
a41p1CbSb_	735	2090.	2090.	1926	164	0	1.34	0.1	4	1
a23B1CbSb_	500	2108.	2108.	1650	458	0	4.46	0.1	4	1
a51B1CbSb_	500	2118.	2118.	1564	554	0	10.18	0.4	5	1

RETURN COST SENSITIVITY

EXAMINE THE SUMMARY OF ALL AC/DC DESIGNS. FOR HELP PRESS F1.

Figure A.15: AC/DC Design Summary Example.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                        AC/DC COST SENSITIVITY

          TO GENERATION COSTS

          TO LINE COSTS

          TO EQUIPMENT COSTS            AC/DC EPNS COST SENSITIVITY

                                    SORT CRITERIA
                                                           RETURN

                              RETURN TO THE AC/DC SUMMARY MENU.
```

Figure A.16: Sensitivity Analysis Options.

More detailed results specifically related to either AC or DC systems are described in Figure A.17 and Figure A.18. A wide range of system performance tables is available for preliminary design comparison including component ratings, cost summaries, margins in meeting the design criteria as well as sensitivity performance.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                        AC DESIGN PERFORMANCE

  AC PERFORMANCE SUMMARY               COST SUMMARY

  GENERATION PERFORMANCE               STATIC VAr COMPENSATION

  LOAD PERFORMANCE                     SHUNT INDUCTANCE

  TEMPORARY OVERVOLTAGES               VOLTAGE PROFILE

  SERIES CAPACITANCE                   LINE PERFORMANCE

  STABILITY PERFORMANCE                COST SENSITIVITY

                                       SORT CRITERIA

                                                           RETURN

                              EXAMINE SUMMARY OF ALL AC DESIGNS.
```

Figure A.17: AC Performance Reports.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel

                        DC DESIGN PERFORMANCE

                     DC PERFORMANCE SUMMARY
                     BIPOLE PERFORMANCE
                     TERMINAL PERFORMANCE
                     COST SUMMARY
                     COST SENSITIVITY
                     DESIGN ANALYSIS
                                    SORT CRITERIA
                                                        RETURN

                              EXAMINE SUMMARY OF ALL DC DESIGNS.
```

Figure A.18: DC Performance Menu.

SENSITIVITY ANALYSIS:

TIDE has the ability to perform a two-dimensional sensitivity scan on any two groups of system parameters. An example of a menu defining a sensitivity analysis with respect to power and distance is shown in Figure A.19. The results of this sensitivity analysis are similar to those shown in section 5.8 and may be analyzed graphically or in a tabular format.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel
Sensitivity Table... x-axis
 CLASS       |PROPERTY        |Step Size

length       |value           |100.0           Number of steps:
Unknown      |Unknown         |Unknown               15
Unknown      |Unknown         |Unknown
Unknown      |Unknown         |Unknown

Sensitivity Table... y-axis
 CLASS       |PROPERTY        |Step Size
                                               Number of steps:
gen          |p_max           |1000.0                20
Unknown      |Unknown         |Unknown
Unknown      |Unknown         |Unknown
Unknown      |Unknown         |Unknown
                                               AC/DC DESIGN EXECUTION

    Location Sensitivity table files: e:\pdexpl
                                     EXECUTE SEARCH
                                      SHOW SEARCH
                                      SUMMARY TABLE
                                          RETURN

                                         RETURN TO THE MAIN MENU.
```

Figure A.19: Sensitivity Analysis Menu.

SETUP:

The setup menu, Figure A.20, controls the overall operation and output of TIDE. Reliability may be enabled or disabled, specified voltage ranges overridden, and the amount of data output in normal operation and sensitivity analysis may be controlled.

```
FILE:MANQC1RA     DESCR:Maniq 5000MW, 600km, 1 Ph, 1.6TOV, 60%SC Red rel
                              T I D E   S E T U P

  Reliability options ON

  Search All V

         P-D TABLE
  Save AC DC best n data separately
  Number of PD designs to save            10
  Save END ONLY

         SCREEN  PRINT
  No network diagrams
  Not print Reliability breakdown
  Not plot SVC/delta/V profile
      SIMULATOR OUTPUT FILES
  Don't Write Availability
  Don't Write States
  Don't Write Delta P
  Write Error Messages        Language and Directories
                              RETURN                 USE F2 FOR MENU OPTIONS
```

Figure A.20: Setup Menu.

APPENDIX B.
DATABASE FOR TIDE SIMULATION EXAMPLES

B.1 Introduction

This appendix summarizes the basic design criteria, equipment data and tolerances used for the studies in this thesis. Note however that TIDE permits the user to modify this basic data to suit the specific practices of a utility. The basic data provided in this appendix are typical of a developed North-American region. Data is provided for the following 8 voltage levels: 1200, 735, 500 and 315 kV AC as well as 800, 600, 450 and 350 kV DC and are divided into three categories, common, AC and DC equipment.

B.2 Design Criteria

The following are representative preliminary transmission design criteria used by the Northeast Power Coordinating Council [81],[79],[80] and by Hydro-Québec [52],[84]. See section 3.3 for a further discussion of these design criteria.

AC design criteria:

1) Maximum permissible temporary overvoltage following load rejection (TOV_{MAX}) ranging from 1.3 to 1.6 p.u. (see Table B.1)
2) Load flow feasibility and steady-state flat voltage profile with 1 line section out of service at full load and 50% of the lines in service at 50% of full load
3) Maintaining dynamic stability for a three-phase 6-cycle fault followed by the loss of a single line section
4) Minimum of two AC lines
5) Maximum SVC rating of 50% of the total generated power

6) Overrate SVC's by 33%

7) One spare transformer at both sending and receiving ends

8) Overrating of series compensation to handle full load with one section line out of service [18].

Table B.1: AC Nominal Voltages and Temporary Overvoltages.

No.	Rated Voltage (kV)	Temporary Overvoltage (p.u.)
1	315	1.6
2	500	1.5
3	735	1.4
4	1200	1.3

DC design criteria:

1) Maximum voltage drop of 10% along the transmission lines

2) Minimum of one DC bipole (single pole operation permitted)

Note that additional DC criteria which were not included in this study are discussed in section B.5.

Design criteria common to both AC and DC:

1) Operate components within ratings

2) Cost transmission losses and expected load outages at 2,000 $/kW

3) Light loading conditions are taken to be 50% of the maximum load

4) The load-duration curve is taken to be linear with a 75% load factor.

B.3 Equipment Data

The equipment data are divided into three parts: common AC/DC, AC and DC equipment. The common equipment consists of the generation, receiving transformers and load. The AC equipment consists of lines, transformers, shunt reactors, series capacitors, static VAr compensators and substations. The DC equipment contains bipolar lines and converter/inverter terminals.

Equipment costs are based on Hydro-Québec's planning department 1991 costs [19]. Costs for additional conductors were extrapolated using data from the EPRI's Transmission Line Reference Book [59]. Reliability data is based on the Canadian Electrical Association's *Equipment Reliability Information System Forced Outage Performance of Transmission Equipment* report spanning equipment years of 1984 to 1988 [20] and CIGRÉ's *Étude sur la Fiabilité des Réseaux CCHT dans le Monde en 1991-1992* for the DC terminals [23]. The reliability data are based on sustained outages which are those exceeding one minute. Outages lasting less than one minute are classified as transient [82]. The components are assumed to be beyond their break-in period and within their normal operating life. The failure frequency and repairs rates are typical average values.

B.3.1 Common Equipment Data

The common equipment data represent the dynamic and electrical characteristics common to both AC or DC systems. There is no cost attributed to system power generation as this is common to all designs but the generation costs are used to evaluate the cost of transmission line losses and DC terminal losses as well as the cost of unreliability.

The generator parameters are shown in Table B.2. For the studies in the thesis, the synchronous and transient reactances were taken to be 0 due to the presence of power system stabilizers [30].

Table B.2: Generator Data

Parameter	Value
Inertia, H	3 kW-sec/kVA
Synchronous reactance, X_d	0 p.u.
Transient reactance, X_d'	0 p.u.
Capacity Cost	2,000 $/kW
Cost variation	25 %
Minimum Power Generated	50 %

The load bus data is summarized in Table B.3. The load bus is modelled as an infinite bus of voltage 1.0 p.u., behind a transformer reactance.

Table B.3: Load Data

Parameter	Value
Inertia, (infinite bus) H	∞ kW-sec./kVA
Receiving end transformer reactance	0.15 p.u.
Load bus voltage	1.0 p.u.

B.3.2 AC Equipment Data

Tables containing the AC equipment data are summarized in Table B.4-Table B.9. For each AC voltage level, four typical conductor sizes were selected with varying resistance and line ampacity, however the line series reactance (x), line shunt susceptance (b), cost variation and reliability data were assumed invariant over the four conductors. For the remaining AC equipment (transformers, shunt reactors, series capacitors, static var compensators and substations), only one type has been defined for each voltage level. The data for series capacitors, Table B.6, is taken to be independent of the voltage level. For the designs considered in this thesis, the shunt reactors were considered to be line connected and the series capacitors were connected in the substations as shown in Figure 3.2. TIDE does provide an option of inverting the order of the series and shunt compensation so that the reactor is connected to the series capacitor rather than the line section.

No	Rated Voltage (kV)	Rated Power (MVA)	Line Parameters (/km)			Cost (/km)		Reliability			
								Line		Terminal	
			R mΩ	X mΩ	B μS	/km K$	Variation (%)	Failure Freq. (per/yr/100km)	Repair Duration (hrs)	Failure Freq. (per/yr)	Repair Duration (hrs)
1	315	870	48.3	368	4.29	215	25	.2988	10.8	.0782	5.1
2		980	40.6			242					
3		1160	31.6			257					
4		1360	23.8			302					
5	500	2770	24.2	337	4.68	425	25	.4038	10.3	.3081	6.1
6		3120	20.3			478					
7		3670	15.8			508					
8		4330	11.9			597					
9	735	6400	12.0	326	4.84	600	25	.1713	7.2	.1172	12.8
10		6800	10.7			634					
11		7500	9.3			675					
12		8200	7.8			742					
13	1200	21000	6.0	298	5.29	1200	25	.1713	7.2	.1172	12.8
14		22000	5.4			1268					
15		24000	4.6			1350					
16		27000	3.9			1485					

Table B.5: AC Transformer Specifications.

No.	Rated Voltage (kV)	Rated Power (MVA)	Reactance X (%)	Cost			Reliability	
				Trans. ($/kVA)	Auxiliary ($/kVA)	Variation (%)	Failure Frequency (per year)	Repair Duration (hrs)
1	315	600	.15	2	1	25	.0511	838
2	500	1100	.15	4	1	25	.0753	486
3	735	1650	.15	7	2	25	.1559	1272
4	1200	2000	.15	12	3	25	.1559	1272

Table B.6: AC Series Capacitor Bank Specifications.

No.	Cost		Reliability	
	$/kVA	Variation (%)	Failure Frequency (per year)	Repair Duration (hrs)
1	40	25	3.38	52.2

No.	Rated Voltage (kV)	Rated Power (MVA)	Cost		Reliability	
			$/kVA	Variation (%)	Failure Frequency (per year)	Repair Duration (hrs)
1	315	100	5	25	.1224	721
2	500	200	7	25	.0621	114
3	735	300	10	25	.1517	1315
4	1200	300	16	25	.1517	1315

Table B.8: AC Static VAr Compensation Specifications.

No.	Rated Voltage (kV)	Rated Power (MVA)	Cost			Reliability	
			SVC $/kVA	Transformer $/kVA	Variation (%)	Failure Frequency (per year)	Repair Duration (hrs)
1	315	100	29	6	25	5.150	51.3
2	500	200	29	10	25	5.150	51.3
3	735	300	29	16	25	5.150	51.3
4	1200	300	29	32	25	5.150	51.3

Table B.9: AC Substation Specifications.

No.	Rated Voltage (kV)	Cost		Reliability	
		per circuit M$/cir.	Variation (%)	Failure Frequency (per year)	Repair Duration (hrs)
1	315	2	25	.01	3000
2	500	5	25	.01	3000
3	735	8	25	.01	3000
4	1200	16	25	.01	3000

B.3.3 DC Equipment Data

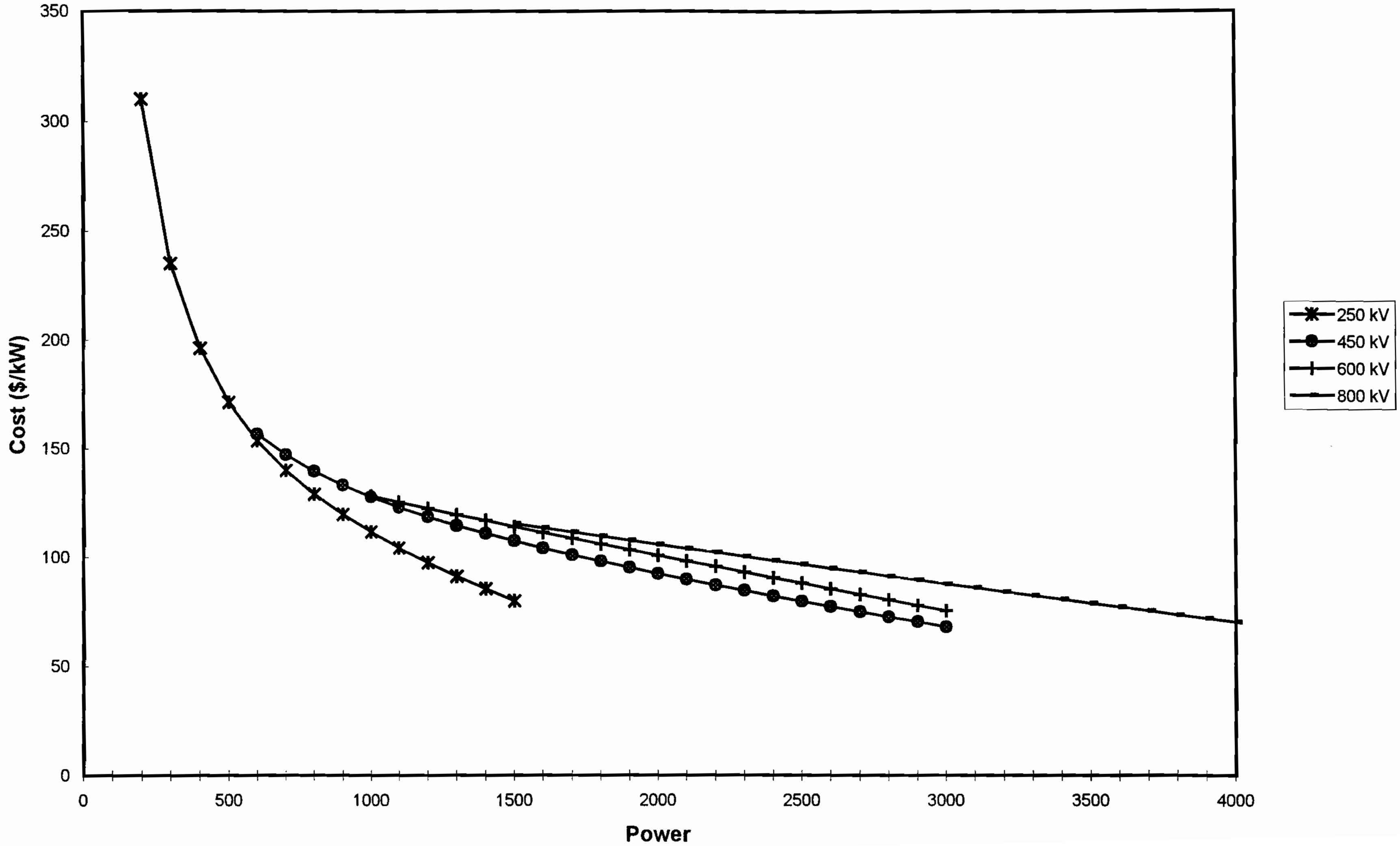
The DC equipment data are summarized in Table B.10 and Table B.11. For each DC voltage level, several conductors were considered [100]. Similarly, DC terminal costs as a function of power are shown in Figure B.1.

No.	Rated Voltage (kV)	Current Rating per cond (kA)	Line Parameters		Cost		Line Reliability		Terminal Reliability	
			# cond. per Cbdl.	R per cond mΩ/km	per km k$/km	Variation (%)	Failure Freq. (per/yr/ 100km)	Repair Duration (hrs)	Failure Freq. (per/yr)	Repair Duration (hrs)
1	250	1300	2	35	351	25	.2988	10.8	.0782	5.1
2		1600	2	26	387					
3		1250	4	42	440					
4	450	1600	2	26	414	25	.4038	10.3	.3081	6.1
5		1800	2	21	422					
6		1250	4	42	454					
7		2000	2	18	480					
8		1400	4	32	523					
9		1600	4	26	568					
10	600	1250	4	42	466	25	.1713	7.2	.1172	12.8
11		1400	4	32	535					
12		1600	4	26	580					
13		1800	4	21	600					
14		1250	6	42	699					
15	800	1250	6	42	719	25	.1713	7.2	.1172	12.8
16		1400	6	32	826					
17		1600	6	26	895					
18		1800	6	21	926					

Table B.11: DC Terminal Specifications.

Terminal	Rated Voltage kV	Losses %	Power		Cost			Reliability	
			Max. MW	Min. MW	Max. M$	Min. M$	Variation (%)	Failure Rate /yr	Repair Duration hrs
1	250	0.75	1500	200	120	62	25	.0915	2296.6
2	450	0.75	3000	600	204	94	25	.2000	1755.2
3	600	0.75	3000	1000	226	128	25	.425	1654.8
4	800	0.75	4000	1500	280	173	25	.5000	1654.8

Figure B.1 DC Terminal Cost as a Function of Power



B.4 Design Knowledge Data

The selection of the nominal AC system voltage ranges used in TIDE is obtained from a lookup table based on system planners' experience. The values shown in Table B.12 were used in TIDE's simulations.

Table B.12: AC Voltage Design Expertise Data Table [38].

Power Range (GW)	Distance Range (km)			
	[0,250)	[250,750)	[750,1250)	[1250,∞)
[0,2)	315kV- 315kV	315kV- 500kV	500kV- 735kV	735kV- 735kV
[2,8)	315kV- 500kV	315kV- 500kV	500kV- 735kV	735kV-1200kV
[8,16)	500kV- 735kV	500kV- 735kV	735kV-1200kV	1200kV-1200kV
[16,∞)	735kV- 735kV	735kV-1200kV	1200kV-1200kV	1200kV-1200kV

Another heuristic provided by the system planner is the maximum angle (θ_{max}) across the system. This angle is used in the design rules to estimate the number of circuits in the system design as seen in equation (D.7). The values used in this thesis are:

Table B.13: Recommended Maximum System Angle.

Fault Type	θ_{max}
Single-Phase	90°
Three-Phase	40°

The selection of the nominal DC system voltage used in TIDE is similarly obtained from a lookup table (see Table B.14). The selection of the DC voltage is based on the power per bipole rather than the total system power.

Table B.14: DC Voltage Design Expertise Data Table.

Minimum Power per Bipole (MW)	Recommended Voltage Level (kV)
<1,000	250
1,000	450
2,000	600
4,000	800

B.5 Additional DC Reliability Design Criteria

Additional design criteria are available in TIDE to ensure that contingencies occurring on the DC system will not adversely affect the AC system to which the DC line is connected. This criteria is expressed as the amount of power that the AC system can lose without being severely affected for the loss of a DC bipolar line. Default values of TIDE are shown in Table B.15 where the maximum power lost below 5,000 MW is fixed at 500 MW, and greater than 500 MW is 10% of the total power.

Another way to reduce the effect of losing a DC line is to overrate the DC erminals to permit the transmission of the extra load. Neither of these two methods, ılthough available in TIDE, were used for the studies conducted for this thesis.

Table B.15: DC Power Loss Due to Loss of a Pole Design Criteria.

Loss type	Power		Loss
	Minimum (MW)	Maximum (MW)	
Fixed loss	1,000	5,000	500 MW
Percent loss	5,000	30,000	10 %

B.6 Simulator Tolerances

The accuracy of the calculations in TIDE are controlled by user specified step-sizes and tolerances (See Table B.16). The amount of compensation required to meet the temporary overvoltage and stability criteria are determined using a compensation step-size of 5%. The tolerance used for calculating the maximum power that can be transmitted for a particular system state is .001 p.u.. The majority of the reliability calculations were performed considering four contingency levels with failures to the fifth level which corresponds to a probability of about 0.1% for the data provided in this appendix.

Table B.16: Tolerances.

Calculation		Tolerance
Compensation Ratings	**Series Capacitance**	5%
	Shunt Reactance	5%
	Static VAr compensator	5%
Maximum Power Transmitted		.001 p.u.
Reliability		4 contingency levels considered

APPENDIX C.
RELIABILITY STATES OF MANICOUAGAN SYSTEM

C.1 Introduction

This appendix contains the full state information used to determine the reliability of the three-line, two-substation, 735 kV AC Manicouagan system (design 1) shown in Table 5.10 of section 5.6. Appendix B contains a summary of the data used to design this system. The states information is contained in the following table. The titles of the columns are as follows: state refers to the state number and reliability cause is the main unreliability cause determined by TIDE. The following elements out of service Tsf S or Tsf R, Line, SVC, Ser C indicate the number of components unavailable in this state for sending and receiving transformers, line sections, static VAr compensators and series capacitors respectively. The state probabilities are the probabilities of being in that state and the cumulative probability is the sum of the probabilities up to and including that state. The delta P's refer to the power reduction of that state in per unit of the total power and can be due to component/thermal or stability limitations.

State	Reliability Cause	Element out of Service				State Probability		Loss-of-Load (Δ P)	
		Tsf S	Tsf R	Line	SVC	(p.u.)	Cumulative (p.u.)	Thermal (p.u.)	Stability (p.u.)
Intact System									
1		0	0	0	0	0.735354	0.735354		
First Level Contingency									
2		1	0	0	0	0.048838	0.784192		
3		0	1	0	0	0.048838	0.833030		
4	Line sect	0	0	1	0	0.002131	0.835161		0.234
5		0	0	0	1	0.129163	0.964325		
Second Level Contingency									
6	Sendtsf	2	0	0	0	0.001081	0.965406	0.332	
7		1	1	0	0	0.003244	0.968649		
8	Line sect	1	0	1	0	0.000142	0.968791		0.234
9		1	0	0	1	0.008578	0.977369		
10	Load tsf	0	2	0	0	0.001081	0.978450	0.332	
11	Line sect	0	1	1	0	0.000142	0.978592		0.234
12		0	1	0	1	0.008578	0.987170		
13	Line sect	0	0	2	0	0.000003	0.987173		1.000
14	Line sect	0	0	1	1	0.000374	0.987547		0.254
15		0	0	0	2	0.009453	0.997000		
Third Level Contingency									
16	Sendtsf	3	0	0	0	0.000008	0.997008	0.666	
17	Sendtsf	2	1	0	0	0.000072	0.997080	0.332	
18	Sendtsf	2	0	1	0	0.000003	0.997083	0.332	

State	Reliability Cause	Element out of Service				State Probability		Loss-of-Load (Δ P)	
		Tsf S	Tsf R	Line	SVC	(p.u.)	Cumula-tive (p.u.)	Ther-mal (p.u.)	Sta-bility (p.u.)
19	Sendtsf	2	0	0	1	0.000190	0.997273	0.332	
20	Load tsf	1	2	0	0	0.000072	0.997345	0.332	
21	Line sect	1	1	1	0	0.000009	0.997354		0.234
22		1	1	0	1	0.000570	0.997924		
23	Line sect	1	0	2	0	0.000000	0.997924		1.000
24	Line sect	1	0	1	1	0.000025	0.997949		0.254
25		1	0	0	2	0.000628	0.998577		
26	Load tsf	0	3	0	0	0.000008	0.998585	0.666	
27	Load tsf	0	2	1	0	0.000003	0.998588	0.332	
28	Load tsf	0	2	0	1	0.000190	0.998778	0.332	
29	Line sect	0	1	2	0	0.000000	0.998778		1.000
30	Line sect	0	1	1	1	0.000025	0.998803		0.254
31		0	1	0	2	0.000628	0.999431		
32	Line sect	0	0	3	0	0.000000	0.999431	1.000	
33	Line sect	0	0	2	1	0.000000	0.999431		1.000
34	Line sect	0	0	1	2	0.000027	0.999459		0.272
35		0	0	0	3	0.000369	0.999828		
Fourth Level Contingency									
36	Send tsf	3	1	0	0	0.000001	0.999828	0.666	
37	Send tsf	3	0	1	0	0.000000	0.999828	0.666	
38	Send tsf	3	0	0	1	0.000001	0.999830	0.666	
39	Send tsf	2	2	0	0	0.000002	0.999831	0.332	

State	Reliability Cause	Element out of Service				State Probability		Loss-of-Load (Δ P)	
		Tsf S	Tsf R	Line	SVC	(p.u.)	Cumula-tive (p.u.)	Ther-mal (p.u.)	Sta-bility (p.u.)
40	Send tsf	2	1	1	0	0.000000	0.999831	0.332	
41	Send tsf	2	1	0	1	0.000013	0.999844	0.332	
42	Line sect	2	0	2	0	0.000000	0.999844	0.332	1.000
43	Send tsf	2	0	1	1	0.000001	0.999845	0.332	
44	Send tsf	2	0	0	2	0.000014	0.999858	0.332	
45	Load tsf	1	3	0	0	0.000001	0.999859	0.666	
46	Load tsf	1	2	1	0	0.000000	0.999859	0.332	
47	Load tsf	1	2	0	1	0.000013	0.999872	0.332	
48	Line sect	1	1	2	0	0.000000	0.999872		1.000
49	Line sect	1	1	1	1	0.000002	0.999873		0.254
50		1	1	0	2	0.000042	0.999915		
51	Line sect	1	0	3	0	0.000000	0.999915	1.000	
52	Line sect	1	0	2	1	0.000000	0.999915		1.000
53	Line sect	1	0	1	2	0.000002	0.999917		0.272
54		1	0	0	3	0.000025	0.999942		
55	Load tsf	0	3	1	0	0.000000	0.999942	0.666	
56	Load tsf	0	3	0	1	0.000001	0.999943	0.666	
57	Line sect	0	2	2	0	0.000000	0.999943	0.332	1.000
58	Load tsf	0	2	1	1	0.000001	0.999944	0.332	
59	Load tsf	0	2	0	2	0.000014	0.999957	0.332	
60	Line sect	0	1	3	0	0.000000	0.999957	1.000	
61	Line sect	0	1	2	1	0.000000	0.999958		1.000

State	Reliability Cause	Element out of Service				State Probability		Loss-of-Load (Δ P)	
		Tsf S	Tsf R	Line	SVC	(p.u.)	Cumulative (p.u.)	Thermal (p.u.)	Stability (p.u.)
62	Line sect	0	1	1	2	0.000002	0.999959		0.272
63		0	1	0	3	0.000025	0.999984		
64	Line sect	0	0	3	1	0.000000	0.999984	1.000	
65	Line sect	0	0	2	2	0.000000	0.999984		1.000
66	Line sect	0	0	1	3	0.000001	0.999985		0.289

APPENDIX D.
SUMMARY OF DESIGN KNOWLEDGE

D.1 Introduction

This appendix contains the basis of TIDE's expert system design module which consists of design knowledge expressed in the form of heuristic rules. The expert system determines initial AC and DC power system skeleton structures consisting of the system topology and estimates of the system parameters. The rules are derived from system planners' heuristics and basic well-established power system principles with certain simplifications and approximations. The initial designs are provided as input to the expert system controlled simulators where they are refined to more precisely define the system performance. (See section 4.8 and Appendix E). The design module containing the design rules is discussed in section 4.7.3 and uses both the design criteria and design expertise databases outlined in section 4.6.

D.2 AC Design

The design of the AC transmission system skeleton structures consists of estimating reasonable *nominal voltage levels*, *number of intermediate circuits*, *number of substations* and *degrees of compensation*. These heuristic rules generate approximate designs based on basic power system formulae and design expertise. The power system representation used in the AC design expert system rules is a lossless, long-line transmission system model. The underlying principles of these rules are discussed below.

The first step in the design estimate is ensuring that an AC system is feasible. To maintain stability of an AC transmission system, the effective line length must be less than the quarter wavelength of the speed of light (300,000/4/f) km where f is the system frequency in Hz [97]. The effective line length (l_{eq}) is equivalent to the line length (l) shortened by the series compensation (SC) expressed as a fraction of 1 and is given by,

$$l_{eq} = l\,(1 - SC) \qquad (km) \qquad \textbf{(D.1)}$$

Therefore the maximum length for a maximum series compensation of SC_{max} is given by,

$$l_{max} = \frac{75{,}000}{f\left(1 - SC_{max}\right)} \qquad (km) \qquad \textbf{(D.2)}$$

Thus, for a 60 Hz system, the maximum equivalent line length is 1,250 km. For longer transmission lines, DC transmission must be used.

If the effective system line length is acceptable, the *nominal system voltage* is estimated relying on the design engineer's experience. Design experts have observed that the system voltage level is tied to the system's power and distance. Typically, higher powers and longer distances necessitate higher voltage levels. To model this in TIDE's design expertise database, recommended minimum and maximum voltage ranges are entered for power and distance intervals. The values used in TIDE's simulation obtained from Hydro-Québec's engineers are shown in Figure B.2. As the most economical voltage is uncertain at this stage, a range of typical voltages is specified. These voltages are then used for the base system designs and to ensure a thorough design process. Sensitivity studies may be performed to consider other voltage levels outside this range.

The *number of intermediate substations* is also approximated by heuristics contained in TIDE's design expertise database. Intermediate substations are required in AC point-to-point systems to install compensation and line protection equipment, to facilitate line maintenance, to limit overvoltages as well as to decrease the severity of system faults. Determining the number of intermediate substations is a balance between the additional cost of an intermediate substation versus the problems associated with excessively long line sections. Very long line sections may result in excessive midpoint voltage regulation as well as increased post-fault line-section-loss contingency severity. Two heuristic parameters control the number of intermediate substations, a maximum allowable distance and a recommended distance between substations. The recommended distance between substations is used as the initial estimate from which sensitivity studies are subsequently carried out in the simulators. The sensitivity studies are bounded by the maximum allowable distance between substations.

The initial estimate of the *number of circuits* is estimated using a reduced form of equation (E.6) using the lossless, long-transmission-line model. As r=0 the propagation constant (γ) and characteristic impedance Z_c of equations (E.9) and (E.10) become,

$$Z_c = \sqrt{\frac{x}{b}\frac{10^{-3}}{10^{-6}}} \qquad \Omega \tag{D.3}$$

$$\gamma = j\beta = j\sqrt{x\,b} \qquad km^{-1} \tag{D.4}$$

for the line impedances x and b expressed in mΩ/km and μS/km respectively. Substituting these values into equations (E.6) and (E.14) gives,

$$P_i = \frac{n_{cir}\ |V_i||V_j|\ \sin(\theta)}{\sqrt{x/b}\ \sinh(j\beta\ l_{eq})} = \frac{n_{cir}\ SIL\ \sin(\theta)}{\sin(\beta\ l_{eq})} \qquad \textbf{(D.5)}$$

for n_{cir} parallel lines, where $\theta = (\delta_j - \delta_i)$ is the angle across the system and the equivalent line length for series compensated lines is approximated by equation (D.1). When the sending-end and receiving-end voltages are assumed to be equal, the transmission line's surge impedance loading (SIL) can be replaced by the product of the voltages divided by the line's characteristic impedance. The propagation constant ß of the uncompensated transmission line can be approximated by,

$$\beta = \frac{2\ \pi\ f}{300{,}000} \qquad km^{-1} \qquad \textbf{(D.6)}$$

where f is the system frequency in Hz.

A heuristic rule recommended by power system planning engineers is that the steady-state system angle should not exceed a certain value. The values chosen for TIDE's database were a maximum angle, θ_{max}, of 90° and 40° for a single-phase and three-phase fault respectively. There is some debate whether 90° is too large but this heuristic seems reasonable to try to load the lines as closely as possible to the SIL, thus maintaining a good voltage stability. These heuristics are stored in the expertise database and may be adjusted by the user.

Therefore, for system angles less than or equal to θ_{max}, the minimum number of circuits (n_{cir}) can be approximated by,

$$n_{cir} \geq \frac{P_{max} \sin(\beta\, l_{eq})}{SIL \sin(\theta_{max})} \qquad \textbf{(D.7)}$$

for the maximum transmitted power (P_{max}).

The initial estimate of the number of circuits is determined for each considered nominal voltage level and line type (hence defining SIL). The number of circuits is further analyzed at a later stage by the expert-system-controlled simulators to ensure that the number of circuits chosen is optimal when considering costs and a more detailed system optimization.

Initial *series capacitance* and *shunt inductance* line compensation values are estimated to meet the system temporary-overvoltage (TOV) criterion. To evaluate the system's TOV for series and shunt compensated lines, the apparent line reactance is approximated by $x\,(1-sc)$ and the apparent line susceptance is approximated by $b\,(1-sl)$. Here sc and bl are the series capacitance and shunt reactance compensation expressed as a fraction of 1. Substituting these values in the lossless expression for the propagation constant (D.4) results in the following expression for the apparent β (β'),

$$\beta' = \beta \sqrt{(1 - sc)\,(1 - sl)} \qquad km^{-1} \qquad \textbf{(D.8)}$$

An expression for the maximum allowable TOV (TOV_{max}) of a lossless compensated transmission line is obtained by substituting (E.10) and (E.13) into (E.30):

$$TOV = \frac{1}{\cos\left(\beta\, l \sqrt{(1 - sc)\,(1 - sl)}\right)} \qquad \textbf{(D.9)}$$

To maintain a VAr balance in the transmission line, the series and shunt compensation estimates are assumed equal (sc = sl). Solving for sc in equation (D.9) results in an initial estimate of,

$$sc = sl = 1 - \frac{\cos^{-1}\left(\frac{1}{TOV_{max}}\right)}{\beta\ l} \qquad \textbf{(D.10)}$$

This VAr balance is only possible, however, if the estimates are positive and below the maximum specified series compensation limit. If the compensation estimate is negative then sc and sl are taken to be zero. For estimates that exceed the maximum series compensation, sc is held at sc_{max} and sl is calculated to maintain the TOV level below TOV_{max} as follows:

$$sl = 1 - \frac{\left(\cos^{-1}\left(\frac{1}{TOV_{max}}\right)\right)^2}{(1 - sc_{max})\ (\beta\ l)^2} \qquad \textbf{(D.11)}$$

D.3 DC Design

Heuristic rules are also used to design DC transmission system skeleton structures which consist of estimated *nominal voltage levels*, *number of terminals* and *bipolar circuits*. These heuristic rules generate approximate designs based on basic power system formulae and design expertise. Line and terminal capacities and reliability constraints are the main considerations in the DC design estimate. The underlying principles of these rules are discussed in this section.

When designing DC systems, TIDE has three options when considering system reliability: ignoring reliability, terminal overrating or increasing the number of bipolar/terminal circuits. The reliability criteria is based on the amount of power than can be lost (P_{rel_loss}) without affecting the integrity of the AC system. The power loss is assumed to be due to n_{rel_out} poles out of service.

In most of the simulations of this thesis, the first option is used where reliability is ignored. Note, however, that the reliability of the system design is still calculated. This method is used as a benchmark for the other initial estimates.

The second reliability option overrates the terminals to meet the reliability criterion resulting in the valve's capacity exceeding the total transmitted power. This method is not normally used in industry due to the increased expense but is available in TIDE to study the impact of this design criterion on the overall system reliability.

The third option is to design the terminals to match the power system load but increase the number of bipolar circuits/terminals so that the loss of n_{rel_out} poles results in a power loss of no more than P_{rel_loss}. This method may result in a large number of bipolar/terminal circuits for weak AC systems making the DC option impractical.

When selecting a base *DC nominal voltage* (V), TIDE provides the user with the choice of investigating all possible system voltages or only those suggested voltage levels based on design engineers' heuristics. The heuristics used for the DC systems are selected solely on the transmitted power rather than on both the power and distance as used in the AC case. The voltage estimates as well as the corresponding powers are stored in TIDE's expertise database (see Table B.14) and are obtained from design engineers. The recommended voltage level is used as a base voltage around which a range of voltage levels is searched to compensate for the uncertainty in the voltage level estimation. The selection of the nominal system DC voltage is less important than for AC systems as the DC simulator is very fast and therefore not so affected by numerical limitations.

The selection of the nominal voltage is based on the line loading expressed as the power per bipole. Thus, an approximation of the number of circuits is necessary when estimating the base system voltage. The number of circuits and system voltage are not independent quantities and thus other voltage levels must be considered to ensure that the optimal voltage level is selected.

The third reliability method is used to approximate the initial number of circuits independently of the voltage level. This criterion is an indication of the strength of the connected AC system which ensures that the AC system will not be adversely affected by this power transmission loss. The number of bipoles/terminals ($n_{cir\_term_{rel}}$) can be expressed as follows:

$$n_{cir\_term_{rel}} \geq \frac{P_{\max}\, n_{rel\_out}}{2\, P_{rel\_loss}} \qquad \textbf{(D.12)}$$

Thus, the line loading can readily be obtained by dividing the total power by this approximate number of required circuits and this loading provides an initial estimate of the voltage level. If this reliability criterion is not used, then all the available DC voltage levels should be considered.

The number of *terminals* at either the sending end or receiving end of the transmission line is based on the terminal's maximum power capability and the reliability criterion.

There is a user-specified practical limit to the size of the terminals of a given voltage level. This value cannot be exceeded and is simply expressed as the transmitted power over the maximum terminal power or,

$$n_{term} \geq \frac{P_{\max}}{P_{term_{\max}}} \quad \textbf{(D.13)}$$

The number of terminals using the second reliability method (terminal overrating) would then be,

$$n_{term_{rel}} \geq \frac{P_{\max} - P_{rel\_loss}}{P_{term_{\max}}} + \frac{1}{2} n_{rel\_out} \quad \textbf{(D.14)}$$

where the terminals are overrated up to the maximum terminal power needed to meet the reliability criterion.

When the third reliability method (increasing the number of circuits) is used the number of terminals (or bipoles) is given from equation (D.12).

The *number of bipolar circuits* (n_{cir}) is determined based on the line rating, the voltage regulation and the reliability criterion. The maximum number of required circuits to meet these criteria for each type of conductor is retained.

The maximum line rating ($I_{cond_{\max}}$) for each conductor is provided in the equipment database and is expressed in current per conductor. The number of bipolar circuits is n_{cir_I} determined to ensure the line rating is not exceeded or,

$$n_{cir_I} \geq \frac{P_{\max}}{2 \; V \; I_{cond_{\max}} \; n_{cbdl}} \quad \textbf{(D.15)}$$

for the maximum power transmitted $P_{\max}$ at a voltage V having n_{cbdl} conductors per bundle.

The number of circuits necessary to ensure meeting the maximum voltage regulation (ΔV) criterion is based on Ohm's law and is expressed as,

$$n_{cir_{\Delta V}} \geq \frac{P_{\max} \; r_{DC} \; l}{2 \; V \; n_{cbdl} \; \Delta V} \qquad \textbf{(D.16)}$$

obtained by rearranging equation (E.37) where r_{DC} is the resistance per km of each conductor.

The number of circuits required to meet the second reliability criteria is given as,

$$n_{cir_{rel}} \geq \frac{1}{2}\left(\frac{P_{\max} - P_{rel\_loss}}{I_{cond_{\max}} \; n_{cbdl} \; V} + n_{rel\_out}\right) \qquad \textbf{(D.17)}$$

The third reliability criterion for the terminals is the same as for the terminals as it is expressed as a function of the reliability function rather than an individual component.

The final number of parallel circuits is then obtained by taking the maximum number of circuits or terminals as follows:

(a) When reliability is not considered:

$$n_{cir\_term} = \max(n_{term}, n_{cir_I}, n_{cir_{\Delta V}}) \qquad \textbf{(D.18)}$$

(b) When components are overrated:

$$n_{cir\_term} = \max(n_{term}, n_{term_{rel}}, n_{cir_I}, n_{cir_{\Delta V}}, n_{cir_{rel}}) \qquad \textbf{(D.19)}$$

(c) When the number of circuits is increased:

$$n_{cir\_term} = \max(n_{cir\_term_{rel}}, n_{term}, n_{cir_I}, n_{cir_{\Delta V}}) \qquad \textbf{(D.20)}$$

APPENDIX E.
ELECTRICAL COMPONENT MODELS AND NETWORK FORMULAE

E.1 Introduction

This appendix contains the basic formulae used in TIDE's simulators to model the electrical and mechanical behaviour of the power system. Each power system component and the formulae which govern their behaviour is discussed. The fundamental network calculations of the load flow, voltage control and transient stability simulators are also outlined.

Due to the large number of simulations required to design and analyze a transmission network, the efficiency of the network representation and calculations is critical in the development of TIDE's design environment. To achieve this high level of efficiency, the electrical network calculations are formulated explicitly to avoid, wherever possible, iterative techniques as found in traditional load flows. This is accomplished by combining parallel line sections, replacing SVC voltage-controlled buses by equivalent shunt reactances and reducing the overall electrical network to a two-bus equivalent network.

Passive electrical components are represented by π-section models as seen in Figure E.1.

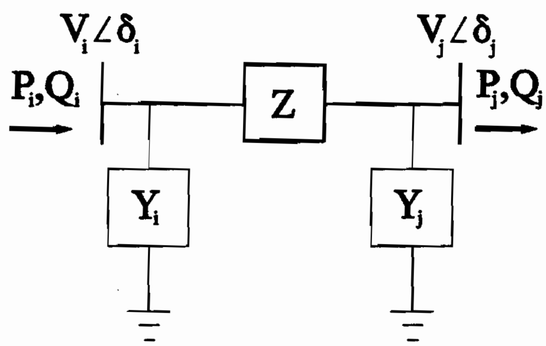


Figure E.1: General π-Model Representation.

ABCD parameters are used for the network calculations which, for the two-bus π-section, are defined as follows [97]:

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_j \\ I_j \end{bmatrix} \qquad \textbf{(E.1)}$$

where:

$$A = 1 + Y_j Z = |A| \angle \alpha \qquad \textbf{(E.2)}$$

$$B = Z = |B| \angle \beta \qquad [\Omega] \qquad \textbf{(E.3)}$$

$$C = Y_i + Y_j + Z Y_i Y_j \qquad [S] \qquad \textbf{(E.4)}$$

$$D = 1 + Y_i Z \qquad \textbf{(E.5)}$$

and the corresponding power flow equations are:

$$P_i = \frac{|A||V_i|^2}{|B|}\cos(\alpha - \beta) - \frac{|V_i||V_j|}{|B|}\cos(\delta_j - \delta_i - \beta) \tag{E.6}$$

$$Q_i = \frac{|A||V_i|^2}{|B|}\sin(\alpha - \beta) - \frac{|V_i||V_j|}{|B|}\sin(\delta_j - \delta_i - \beta) \tag{E.7}$$

E.2 Network Components

The models used to represent the network components for the AC and DC systems are now discussed. These models are used in TIDE's simulators to approximate the physical behaviour of the power system. The models are not detailed but have sufficient accuracy to represent the system behaviour for preliminary transmission planning.

E.2.1 AC Network Components

The AC component models contained in TIDE are: generation, transformers (TSF), transmission lines (Line), series capacitors (SC), shunt reactors (SL), static VAr compensators (SVC), load and substations (SS). The reader is referred to Table E.1 for the steady-state and stability models of each of these components which are described in the following sections. These AC models are used in the voltage control, load flow, stability and reliability calculations.

The *generation* electrical model consists of a voltage source $E\underline{/\delta}$ behind a synchronous (jx_d) or transient (jx_d') reactance and produces the real power P. The internal voltage magnitude E is assumed to remain constant in steady-state and during transients. Various generator angles such as the steady-state (δ_o), maximum swing or transient (δ_{max}) and steady-state post-fault (δ_p) generator angles are calculated. (See Figure E.5). The mechanical power supplied to the generator is assumed to remain constant in steady-state as well as during the transient as the governor will not have had time to react during the fault. The output power is assumed to be provided by all generating units and therefore the generator impedance and inertia are held constant despite changes in generation for heavy and light loading conditions. In steady-state, the terminal voltage (V) is assumed to be held at 1 p.u. by a voltage regulator which adjusts the internal voltage (E) accordingly.

The mechanical behaviour of the generator is modelled by the classical swing equation,

$$\frac{d^2\delta}{dt^2} = \frac{P_m - P(\delta)}{2H} \, 2 \pi f \quad rad/s^2 \qquad \textbf{(E.8)}$$

where δ is the angle across the system in radians, H is the generator's inertia constant expressed in seconds, P_m is the input mechanical power in pu, and $P(\delta)$ is the output electrical power in pu. In steady-state, $P_m = P(\delta)$ but, during transients, P_m is unequal to $P(\delta)$, resulting in oscillations of the generator angle, δ, and in potential system instability.

Transformers are represented by their leakage reactances (x_{tf}) and the magnetising current is neglected. During temporary overvoltages the transformer cores may become saturated and absorb large amounts of VArs which assist in reducing overvoltages. This phenomenon is not modelled which tends to overestimate the amount of compensation required for TOV calculations. On-load tap-changers (OLTC) are not considered which tend to increase the SVC ratings and the effect of line regulation. All transformers (including spares) are assumed to be on line despite system loading and thus the overall reactance remains constant unless transformers are removed for the contingency analysis in the reliability calculations. Transformer losses are neglected.

The *transmission lines* are represented by a long-line distributed parameters model based on the basic electrical data which are the series resistance per bundle (r) and reactance (x) both in mΩ/km and the shunt susceptance (b) in μS/km. The line's characteristic impedance (Z_c) and propagation constant (γ) are defined as follows:

$$Z_c = \sqrt{\frac{(r + jx)\,10^{-3}}{jb \quad 10^{-6}}} \qquad \Omega \qquad \textbf{(E.9)}$$

$$\gamma = \alpha + j\beta = \sqrt{(r + jx)\, jb\, 10^{-9}} \qquad km^{-1} \qquad \textbf{(E.10)}$$

where α is the attenuation constant and β is the phase or propagation constant.

The electrical model of a transmission line of length l, in km, is calculated as a π-equivalent where the values of the equivalent series impedance (Z) and shunt admittance are given by,

$$Z = \frac{(r + jx)\, l}{1000} \frac{\sinh(\gamma\, l)}{\gamma\, l} \qquad \Omega \qquad \textbf{(E.11)}$$

$$Y = \frac{jb\, l}{10^6} \frac{\tanh\left(\frac{\gamma\, l}{2}\right)}{\frac{\gamma\, l}{2}} \qquad S \qquad \textbf{(E.12)}$$

The transmission lines are modelled using the ABCD parameters in TIDE's simulators as follows:

$$A = D = \cosh(\gamma\, l) \qquad p.u. \qquad \textbf{(E.13)}$$

$$B = Z_c \sinh(\gamma\, l) \qquad \Omega \qquad \textbf{(E.14)}$$

$$C = \frac{1}{Z_c} \sinh(\gamma\, l) \qquad S \qquad \textbf{(E.15)}$$

AC transmission lines are limited by thermal loading, excessive voltage drop or stability limitations. Transmission line loading is usually expressed as a function of the surge impedance loading (SIL) which occurs when VAr absorbtion in the transmission line's series reactance equals the VAr generation of its shunt capacitance [59].

The *series capacitors* are represented by their reactance (SC) and losses are ignored. Series capacitances are expressed in terms of the percentage of the line's reactance per km, x_{line}. The total amount of series reactance for a line section of length of l (km) with a series compensation of sc (p.u.) is:

$$SC = sc\; x_{line}\; l \qquad \Omega \qquad \textbf{(E.16)}$$

The series capacitors are assumed to remain in service on the non-faulted sections during system faults.

Shunt reactors are modelled by their reactance (SL) and losses are ignored. They are assumed to be in service for all the operating conditions studied in TIDE. Shunt reactors are expressed in terms of the percentage of the line's susceptance b. The total amount of shunt reactance for a line section of length of l (km) with a shunt reactance of sl (p.u.) is:

$$SL = sl\ b\ l \qquad\qquad S \tag{E.17}$$

The ABCD representation of the series capacitor and shunt reactor are expressed below for the left hand side compensation (See Figure E.2). (The right hand compensation is obtained by exchanging parameters A and D).

$$A = 1 + jSC\ jSL \tag{E.18}$$

$$B = jSL \qquad\qquad \Omega \tag{E.19}$$

$$C = jSC \qquad\qquad S \tag{E.20}$$

$$D = 1 \tag{E.21}$$

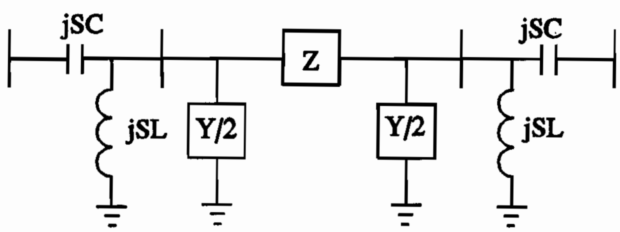


Figure E.2: AC Transmission Network with Compensation.

Static VAr compensators are modelled as voltage sources during steady-state operation to maintain a flat voltage profile of 1 p.u. for heavy and light loading conditions. The amount of reactive power generated by the voltage source is converted into an equivalent shunt capacitance so that the network can be reduced to an overall π-equivalent. The first step in this calculation is to represent the transmission line sections, shown in Figure E.2, as well as the series and shunt line compensation using ABCD parameters as previously described. These three π-sections are combined into an equivalent π-section representing the compensated line section by multiplying the three

ABCD matrices. Subsequently the parallel line sections are then combined to obtain equivalent ABCD matrices for each combined line section as shown in Figure E.3.

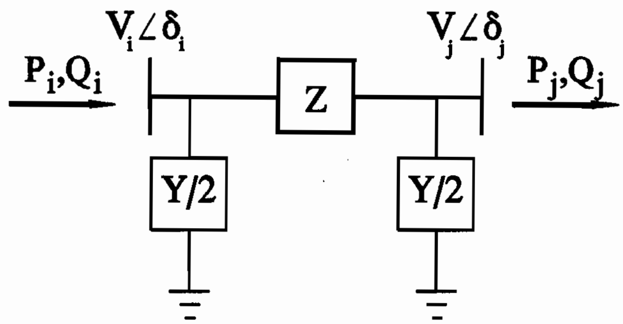


Figure E.3: SVC Modelling for Voltage Control.

Each π-section is considered separately when determining the amount of reactive power (Q_i) necessary to hold the bus voltages (V_i, V_j) at 1 p.u.. An expression for Q_i is obtained by solving (E.6) equation for $\delta_j - \delta_i - \beta$ as follows:

$$\delta_j - \delta_i - \beta = \cos^{-1}\left(\frac{-P_i|B| + |A||V_i|^2\cos(\alpha-\beta)}{|V_i||V_j|}\right) \quad \textbf{(E.22)}$$

and substituting it into (E.7) to obtain:

$$Q_i = \frac{|A||V_i|^2}{|B|}\sin(\alpha-\beta) - \frac{|V_i||V_j|}{|B|}\sin\left(\cos^{-1}\left(\frac{-P_i|B| + |A||V_i|^2\cos(\alpha-\beta)}{|V_i||V_j|}\right)\right) \quad \textbf{(E.23)}$$

Similarly, from δ_j-δ_i, the injected real and reactive power (P_i and Q_j) at the receiving end of the π-section are calculated. For example, P_j is given by,

$$P_j = \frac{|A||V_j|^2}{|B|}\cos(\alpha-\beta) - \frac{|V_i||V_j|}{|B|}\cos\left(\cos^{-1}\left(\frac{-P_i|B| + |A||V_i|^2\cos(\alpha-\beta)}{|V_i||V_j|}\right)+2\beta\right) \quad \textbf{(E.24)}$$

The receiving end reactive power Q_j can be obtained from equation (E.23) by interchanging the indices i and j. Q_i and Q_j are the reactive powers necessary to support the desired voltage at either end of the π-section.

Figure E.4 shows the single-line diagram when many π-sections in series are considered. The SVC, shown as a voltage source, supplies the reactive power necessary to maintain the desired voltage level. The injected reactive power $Q_{SVC,i}$ at bus i is seen

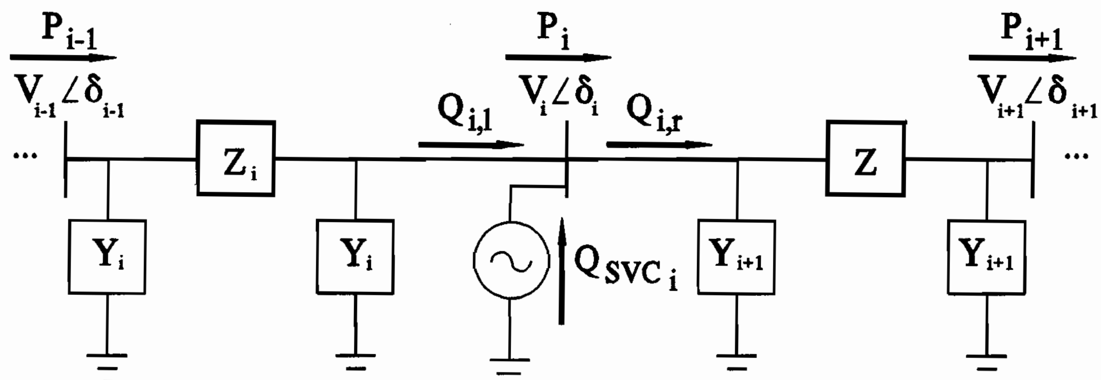


Figure E.4: SVC Modelling for Voltage Control.

to be the difference between $Q_{i,l}$ and $Q_{i,r}$. This reactive power is converted into an equivalent admittance given by:

$$Y_{SVC} = \frac{Q_{SVC}}{|V_i|^2} \quad \textbf{(E.25)}$$

The admittance at each SVC controlled bus is calculated for each intermediate bus across the network starting with the generator bus and working towards the load bus. The generator angle is taken to be the reference for these calculations. Either the maximum or minimum power is used depending on whether the heavy or light loading conditions are being studied. The values of Y_i and Z_i may also change for certain line sections depending on the contingency being considered. It is necessary to recalculate the power entering and leaving each π-section across the system to account for the system losses. Using an ABCD representation for the SVC's impedance, the complete network may be reduced to one equivalent π-section which can be used in load flow and stability calculations. The amount of injected SVC required to maintain a flat voltage profile must be recalculated for each loading condition.

An overall capacitive and reactive SVC rating is determined for each loading condition by considering the reactive power requirements for each bus. The largest rating at any one particular intermediate bus is used for all the intermediate buses as the conditions of this bus, such as the loss of a line section, can occur anywhere on the system. The sending and receiving end SVC requirements are calculated separately as their ratings will differ from the intermediate substations due to the effect of the sending and receiving transformers. Thus, the overall steady-state SVC requirements for a loading condition (k) are the sums of the minimum and maximum ratings for the sending bus (1), load bus (n_{ss+2}) and worst-case intermediate buses (i=2 to n_{ss+1}) as seen below.

$$Q_{SVC_{\max,k}} = Q_{SVC_{1,k}} + n_{ss} \max_{i=2,n_{ss+1}} (Q_{SVC_{i,k}}) + Q_{SVC_{(n_{ss}+2),k}} \quad for \ Q_{SVC_{i,k}} \geq 0 \qquad \textbf{(E.26)}$$

$$Q_{SVC_{\min,k}} = Q_{SVC_{1,k}} + n_{ss} \min_{i=2,n_{ss+1}} (Q_{SVC_{i,k}}) + Q_{SVC_{(n_{ss}+2),k}} \quad for \ Q_{SVC_{i,k}} \leq 0 \qquad \textbf{(E.27)}$$

The overall system SVC ratings ($Q_{SVC_{\max}}$, $Q_{SVC_{\min}}$) used for costing are the maximum (or minimum) SVC ratings of the heavy loading (HL), the light loading (LL), heavy loading with one line section out (N-1) and the stability rating.

$$Q_{SVC_{\max}} = \max \left(Q_{SVC_{\max,HL}} \, , \, Q_{SVC_{\max,LL}} \, , \, Q_{SVC_{\max,N-1}} \, , \, Q_{SVC_{stability}} \right) \qquad \textbf{(E.28)}$$

$$Q_{SVC_{\min}} = \min \left(Q_{SVC_{\min,HL}} \, , \, Q_{SVC_{\min,LL}} \, , \, Q_{SVC_{\min,N-1}} \right) \qquad \textbf{(E.29)}$$

The transient SVC ratings are discussed in the following section which deals with stability calculations.

The *load* is modelled as an infinite bus whose voltage and frequency is assumed to be held constant at 1 p.u. The load bus is used as the system reference bus.

Substation and corridor outages are only considered for reliability purposes.

Table E.1: Steady-State and Transient AC Component Models.

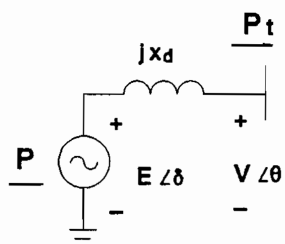
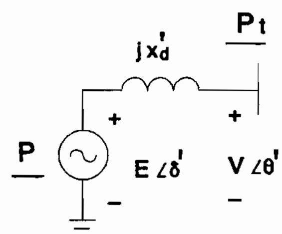
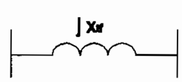
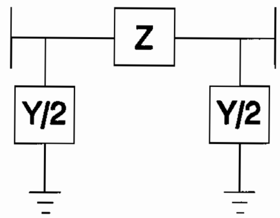
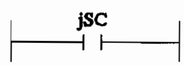
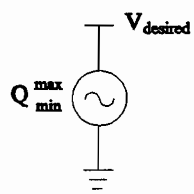
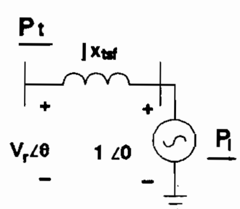
Component	Steady-State	Transient
Generation		
Transformer		same

Table E.1: Steady-State and Transient AC Component Models.

Component	Steady-State	Transient
AC Transmission Line		same
Series Capacitor		same
Shunt Reactor		same
Static VAr Compensator		
Load		same
AC substation	Bus	same

E.2.2 DC Components

The DC components models contained in TIDE are: generation, terminals, transmission lines and load. The reader is referred to Table E.2 for the steady-state models of each of these components.

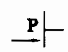
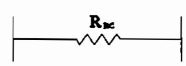
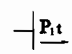
The DC *generation* model is simply an ideal voltage source which supplies DC real power (P) at a voltage of 1 p.u. to the terminals.

DC *terminals* are modelled as a bus with losses. The output voltage is assumed to be 1 p.u. DC at the sending end terminal.

Only the resistive characteristics of the DC *transmission lines* are considered and thus only line voltage regulation and thermal restrictions are specified. The transmission line resistance r_{DC} is expressed in Ω/km/conductor.

The *load* model is taken to be a sink which operates at unity power factor and has no voltage support. It is assumed that the reactive support necessary to maintain the voltage is contained in the terminals although not explicitly calculated.

Table E.2: Steady-State DC Component Models.

Component	Steady-State
Generation	
DC Terminal	Bus (with losses)
DC Transmission Line	
Load	

E.3 Network Calculations

E.3.1 AC Network Calculations

The network calculations for the network's temporary overvoltages (TOV), load flow, and stability are discussed in the following section.

Temporary overvoltages are readily calculated from the equivalent system network ABCD parameters. The intact network is used for the TOV calculations with the SVC's floating (no voltage support). TOV's occur when there is an unexpected loss of load and there is an overvoltage at the receiving end of the transmission line which remains temporarily energized. It can be seen from equation (E.1) that when the load is removed from the receiving-end of the transmission line (I_j=0) the TOV or the ratio of the receiving-end voltage and the sending-end voltage magnitudes is simply given by:

$$TOV = \frac{|V_j|}{|V_i|} = \frac{1}{|A|} \qquad \textbf{(E.30)}$$

where A is defined by the ABCD parameters of the equivalent π network. To control the system TOV it may be necessary to add shunt inductance and series capacitance to the system.

Load flow feasibility is determined by solving equation (E.22) for the ABCD parameters for the complete network. The sending and receiving voltages in steady-state are held at 1 p.u. whereas in the transient stability calculations, the voltage during the fault is permitted to decrease if the SVC's are at their maximum limit. If no solution exists to (E.22), then the load flow is infeasible and TIDE will attempt to increase the capability of the network by increasing the level of series compensation or the number of transmission lines.

The *stability calculations* are based on the equal-area criteria where one machine swings against an infinite bus. This permits the first swing stability of a system to be determined explicitly without numerically integrating the swing equation (E.8). When the system is in steady-state, the mechanical power generated by the turbine (P_m) equals the electrical power P(δ) supplied to the system. The pre-fault system for the stability calculations is assumed to be in steady-state, transmitting the maximum system power as seen in Figure E.5. The data used for this diagram was taken for a three-phase fault for the Manicouagan system, design 1 of Figure 5.2 in the fault type sensitivity analysis. The pre-fault angle across the system δ_o is calculated from equation (E.22) referenced to bus j (ie. δ_j=0°).

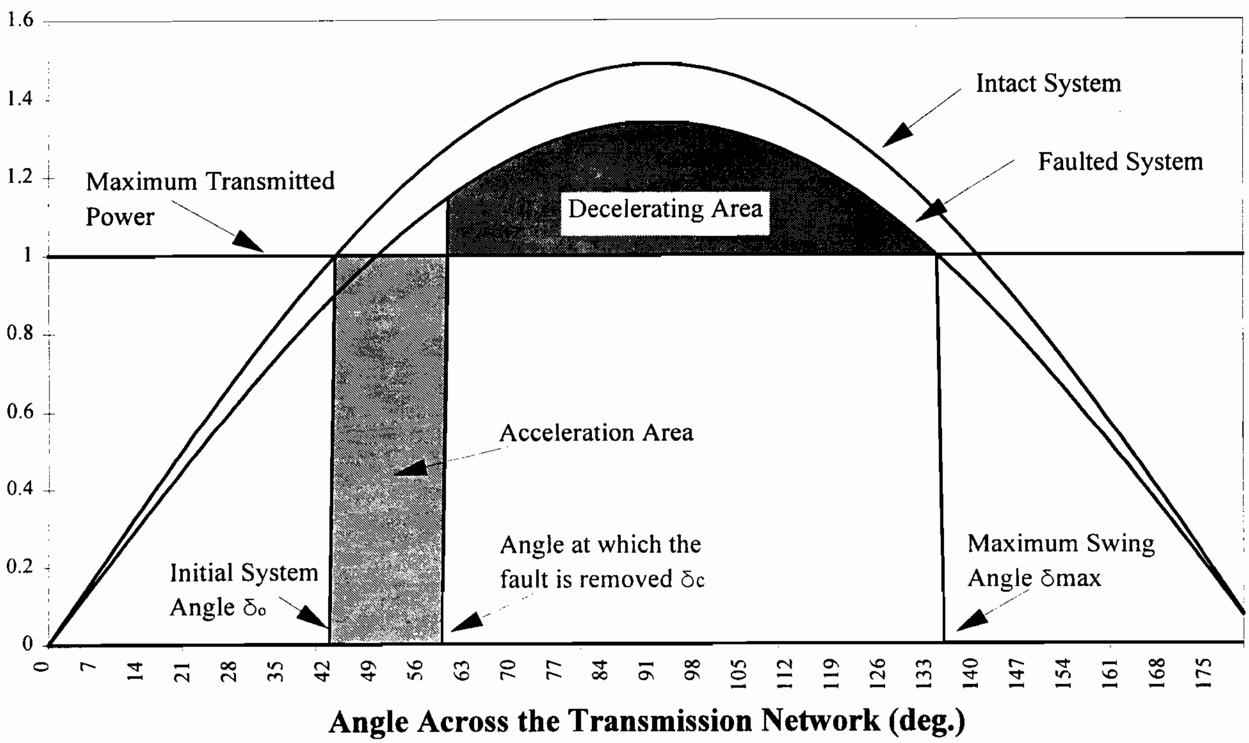


Figure E.5: Equal-Area Stability Curves.

When a three-phase fault is applied to the generator bus, the mechanical power supplied to the system is assumed to remain constant for the duration of the fault whereas the transmitted electrical power is reduced to zero. This power imbalance causes the generator to accelerate. The fault is cleared at time t_c and the new generator rotor angle can be obtained by integrating the swing equation (E.8) with respect to time giving a clearing angle δ_c of:

$$\delta_c = \frac{\pi f P_m}{H} \frac{t_c^2}{2} + \delta_0 \tag{E.31}$$

as seen in Figure E.5. For the system to be stable, the mechanical energy supplied to the generator's rotor during the fault must be able to be absorbed to decelerate the rotor back to synchronous speed. This can be expressed by the following inequality,

$$A_{acc} = \int_{\delta_0}^{\delta_c} (P_m - P_e) d\delta \leq \int_{\delta_c}^{\delta_{max}} (P_e - P_m) d\delta = A_{dec} \tag{E.32}$$

Integrating the left-hand side of this relation and representing the faulted condition where P_e is equal to zero, results in an expression for the accelerating energy supplied to the generator's rotor during the fault, as seen in Figure E.5, given by,

$$A_{acc} = P_m(\delta_c - \delta_0) \tag{E.33}$$

Similarly, integrating the right-hand-side of (E.32) gives the following expression for the decelerating energy:

$$A_{dec} = \left(\frac{|A_{af}||V_i|^2}{|B_{af}|} \cos(\alpha_{af} - \beta_{af}) - P_m \right) (\delta_{max} - \delta_c) + \frac{|V_i||V_j|}{|B_{af}|} (\sin(\delta_{max} + \beta_{af}) - \sin(\delta_c + \beta_{af})) \quad \textbf{(E.34)}$$

where:

$$\alpha_{max} = \pi - \beta_{af} - \cos^{-1}\left(\frac{P_e |B_{af}| + |A_{af}||V_s|^2}{|V_s||V_r|} \right) \quad \textbf{(E.35)}$$

TIDE's simulators add series compensation to decrease the system's initial operating angle and increase the decelerating area by increasing the system's power transfer capabilities. This process is iterative and continues until the system is stabilized or the maximum series compensation is reached.

As the post-fault system is usually degraded by the loss of a line section, the ABCD parameters used in the deceleration calculation, denoted by the subscript af, are used. It can be seen from Figure E.5 that the power curve is reduced which results in a smaller decelerating area. The new steady-state angle will also increase.

The amount of SVC that can be used to stabilize a system is limited by the following practical considerations:

1) When the equivalent π electrical model of the network has a negative reactance, as this will lead to a virtual zero somewhere in the system.

2) When the voltages during the transient exceed a user specified value, usually 1.0 p.u. as the SVC becomes inductive at greater voltages.

'hese conditions arise when system lines are heavily loaded and large amounts of SVC re required to stabilize the system. If these conditions are violated, the system is rejected y TIDE.

E.3.2 DC Network Calculations

The DC network calculations consist of determining the line loading, the voltage regulation over the DC transmission line, as well as the system losses. As previously seen in this appendix, the DC transmission line is represented as a resistance r_{DC} expressed in Ω/km/conductor.

The transmission *line loading* is the conductor current expressed in amperes. For a transmitted power of P MW operating at a pole to ground voltage of V, the transmission line loading are given by,

$$I_{cond} = \frac{P}{2\ V\ n_{cir}\ n_{cbdl}} \qquad kA \qquad \textbf{(E.36)}$$

for a line having n_{cbdl} conductors per bundle and n_{cir} bipoles.

The *voltage regulation* (ΔV) across a transmission line of length l is obtained by simply multiplying the conductor current by the conductor's resistance:

$$\Delta V = I_{cond}\ r_{DC}\ l = \frac{P\ r_{DC}\ l}{2\ V\ n_{cir}\ n_{cbdl}} \qquad kV \qquad \textbf{(E.37)}$$

The DC *losses* are comprised of two parts, line losses and terminal losses. The line losses P_{Lloss} are given as follows:

$$P_{loss} = 2\ n_{cir}\ n_{cbdl}\ I^2_{cond}\ r_{DC}\ l = \frac{P^2\ r_{dc}\ l}{2\ V^2\ n_{cir}\ n_{cbdl}} \qquad MW \tag{E.38}$$

Included in the terminal losses (P_{Tloss}) are thyristor valve, transformer, AC filter and smoothing reactor losses which are approximated as a specified percentage (k_{Tloss}) of the station rating. All of the DC converter/inverter stations are given the same rating which equal the maximum power transfer of the system. Thus, the terminal losses can be expressed as a percentage of the total transmitted power (P), rather than the individual converter rating:

$$P_{Tloss} = 2\ P\ k_{Tloss} \qquad MW \tag{E.39}$$

The total DC losses are the sum of the line and terminal losses:

$$P_{DC\ loss} = P_{Lloss} + P_{Tloss} \qquad MW \tag{E.40}$$

APPENDIX F.
COSTING FORMULAE

F.1 Costing

This appendix contains the basic formulae which are used in TIDE's costing expert system. The reader is also referred to a discussion of the costing module in section 4.7.5 and a summary of the costing formulae in the component cost summary table, Table 4.7. The actual costs used in TIDE's simulations are shown in Appendix B. Costing in TIDE only considers the capital costs of each component and of the system losses. These costs are used mainly for design comparison purposes rather than to find the actual overall costs which would also include equipment life, inflation, interest during construction and the time cost of money. The method of calculating the costs for the AC and DC system designs is now discussed.

F.1.1 AC Costing

The overall cost of the AC design is comprised of the cost of losses (C_{loss}), the cost of unreliability (C_{unrel}) and the component costs, as shown below:

$$\begin{aligned} C_{design} = C_{loss} + C_{unrel} + TC_{tsf} + TC_{line} + \\ TC_{sc} + TC_{sl} + TC_{SVC} + TC_{ss} \end{aligned} \qquad \textbf{(F.1)}$$

where the component costs are made up of the transformer (TC_{tsf}), line (TC_{line}), series capacitance (TC_{sc}), shunt inductance (TC_{Sl}), static VAr compensation (TC_{SVC}) and the substation (TC_{ss}) costs.

The *generator* costs are not included in the cost comparisons since they are ommon to all designs. The cost of generation is used, however, in assigning a value to he system losses and to the cost of unreliability.

The total system *losses* are obtained as described in section E.2. The cost of losses s the product of the system losses (P_{loss}) multiplied by the generation cost (C_{gen}) or,

$$C_{loss} = P_{loss}\ C_{gen} \qquad \textbf{(F.2)}$$

vhere the C_{gen} is specified in M$/MW

Expected-power-not-supplied (EPNS) is the system *unreliability* index used to ssign a cost to the unreliability of the system. The method to calculate the EPNS index s discussed in sections 4.8.5.4 and 5.5. The cost assigned to system unreliability is liscussed in section 5.6. The overall cost of unreliability is the product of the EPNS and he cost of unreliability, C_{EPNS}, that is,

$$C_{unrel} = EPNS\ C_{EPNS} \qquad \textbf{(F.3)}$$

The *transformer* costs are based on the number of transformers and their per-unit osts. The per-unit costs are composed of two components, the cost of the transformer tself (C_{tsf}) and the auxiliary cost (C_{aux}), both expressed in $/kVA. The transformer rating 1 kVA (S_{tsf}) is contained in TIDE's equipment database and the number of transformers n_{tsf}) is determined based on the system requirements, as well as the spare allocation. The pare allocation may be based on the N-1 criterion or on a probabilistic spare allocation lgorithm (See section 4.8.5.6). The overall cost for the sending and receiving ansformers is given by,

$$TC_{tsf} = 2\ n_{tsf}\ S_{tsf}\ (C_{tsf} + C_{aux}) \quad \textbf{(F.4)}$$

where the cost of the step-up and step-down transformers is assumed to be equal.

The *AC transmission lines* are costed based on the number of three-phase circuits (n_{cir}), the length of the transmission line (l) and the cost of the line (C_{cir}) given in k$/km/circuit. The cost is assumed to be uniform for the whole transmission line and cost fluctuations due to topology or routing considerations are not considered. Therefore, the line cost is,

$$TC_{line} = n_{cir}\ l\ C_{cir} \quad \textbf{(F.5)}$$

The cost of the *series compensation* is estimated by the total reactive power rating (Q_{sc}) multiplied by the component cost (C_{sc}) as seen below,

$$TC_{sc} = Q_{sc}\ C_{sc} \quad \textbf{(F.6)}$$

where the component cost is expressed in $/kVA. Series capacitors are rated for full power steady-state operation with one line out (N-1). Therefore, the total reactive power rating for n_{cir} is given by,

$$Q_{sc} = \frac{n_{cir}\ SC\ P^2}{(n_{cir} - 1)^2\ V^2} \quad \textbf{(F.7)}$$

The cost of the *shunt inductance* is estimated by its total reactive power rating (Q_{sl}) multiplied by its component cost (C_{sl}) or,

$$TC_{sl} = Q_{sl}\, C_{sl} \tag{F.8}$$

where the component cost is expressed in \$/kVA. The reactive power rating of the shunt inductance is calculated from the product of the total shunt reactance per circuit (SL, equation (E.17)) expressed in siemens, by the number of circuits (n_{cir}) for the nominal voltage V,

$$Q_{sl} = n_{cir}\; SL\; V^2 \tag{F.9}$$

The cost of the *static VAr compensators* is determined from the amount of reactive power generated by the SVC. The cost of the SVC is divided into two parts, the reactive source (capacitance and inductance) and the step-up transformer. Equations (E.28) and (E.29) are used to determine the maximum and minimum SVC ratings. The step-up transformer rating is based on the largest reactive power supplied by the SVC, either $Q_{SVC_{max}}$ or $Q_{SVC_{min}}$. The rating of the reactive source is determined based on the capacitive and inductive ranges. In a normal case where $Q_{SVC_{max}} > 0$ and $Q_{SVC_{min}} < 0$ the reactive-source cost is the total of the reactive elements. If the network is very inductive ($Q_{SVC_{max}} > Q_{SVC_{min}} \geq 0$) then reactive-source costs are based solely on $Q_{SVC_{max}}$. Similarly, for capacitive networks ($Q_{SVC_{min}} < Q_{SVC_{max}} \leq 0$) reactive-source costs are based solely on $Q_{SVC_{min}}$. Thus, the SVC cost can be expressed as,

$$TC_{SVC} = (\max(Q_{SVC_{max}},0) + \min(Q_{SVC_{min}},0))\, C_{SVC} + \max(|Q_{SVC_{max}}|,|Q_{SVC_{min}}|)\, C_{SVC_{tsf}} \tag{F.10}$$

Finally, the cost of the *substations* is approximated as a function of the number of substations (n_{SS}) and the number of line terminations. The substation cost (C_{SS}) is expressed in \$/cir. The overall cost of substations is given as follows,

$$TC_{SS} = 2\, n_{cir}\, (n_{ss} + 1)\, C_{SS} \tag{F.11}$$

F.1.2 DC Costing

The overall cost of the DC design is comprised of the cost of losses, unreliability and the component costs as shown below:

$$C_{design} = C_{loss} + C_{unrel} + TC_{line} + TC_{term} \tag{F.12}$$

The total DC system *losses* are calculated using equation (E.40) which includes both line and terminal losses. The cost of losses is the product of the system losses (P_{DC_loss}) and by the generation costs (C_{gen}) or,

$$C_{loss} = P_{DC\_loss}\, C_{gen} \tag{F.13}$$

where the C_{gen} is specified in M\$/MW.

Similarly to the AC calculations, the *DC reliability costs* are obtained from the product of the EPNS and the cost of unreliability,

$$C_{unrel} = EPNS\; C_{EPNS} \tag{F.14}$$

The DC *transmission lines* are costed based on the number of bipolar circuits (n_{cir}), the length of the transmission line (l) and the cost of the line (C_{cir}) given in k$/km/bipole. Similarly to the AC costing, the line cost is assumed to be uniform along the whole transmission line and cost fluctuations due to topology or routing considerations are not considered. Therefore, the DC line cost is,

$$TC_{line} = n_{cir}\ l\ C_{cir} \qquad \textbf{(F.15)}$$

The DC *terminal* costs include the AC/DC converter/inverter equipment, the AC switch-yard, filters, compensation equipment and transformers all expressed in M$/MW. Terminals are custom designed to meet the desired power ratings as shown in Figure B.1. Therefore their cost is determined as a function of their rating and voltage,

$$TC_{term} = 2\ n_{term}\ C_{term} \qquad \textbf{(F.16)}$$