INTELLIGENT POWER SYSTEM DESIGN

by

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ABSTRACT

In this thesis, the concept of an intelligent system for the design and planning of electric power systems is developed. Such a system serves to preserve the vast body of power system design knowledge by identifying, structuring and consolidating it into one easily accessible source. The intelligent system can then be used to support experienced power system planners or for training purposes. The main planning and design activities considered include the design of a complete power system or of specific subsystems such as a substation or a transmission corridor. The principal features and main components of this general intelligent system, called PSIDE, are delienated.

A general methodology and a design tool were then devised for modelling and using this kind of knowledge. The object-oriented strategy was found to be the most suitable due its powerful capabilities to naturally represent the structure and behaviour of power systems. Thus, PSIDE is based on object-oriented knowledge models for design tasks such as point-to-point transmission design, insulation coordination as well as protection system and substation design.

In order to validate the proposed concepts as well as the object-oriented paradigm adopted for their realization, a substation design module (SIDE) was fully developed and tested.

RÉSUMÉ

Cette thèse porte sur la notion d'un système intelligent pour la conception et la planification de réseaux électriques. Ce système sert à maintenir la masse des connaissances existantes dans le domaine de conception de réseaux électriques en identifiant, structurant et consolidant cette base dans une source facilement accessible. Le système intelligent peut donc être utilisé comme support pour les ingénieurs d'application expérimentés ou comme outil de formation. Les activités principales considérées incluent la conception d'un réseau entier ou de sous-systèmes plus spécifiques tels qu'un poste ou un coridor de transport. Les caractéristiques et les composantes majeures de ce système intelligent, nommé PSIDE sont brièvement décrites.

Afin de modéliser et d'utiliser ce type de connaissances dans des applications servant à la planification des réseaux, on a élaboré une méthodologie générale et un outil de conception. Les stratégies fondées sur l'analyse "orientée-objet" semblent être les plus aptes à représenter naturellement la structure et le comportement des reséaux électriques. Ainsi, PSIDE permet d'effectuer des tâches telles que la conception de lignes de transport, la coordination de l'isolement, la conception des systèmes de protection et des postes.

Afin de valider les concepts proposés ainsi que le paradigme "orientée-objet", un module pour la conception des postes nommé SIDE a été entièrement développé et testé.

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LIST OF ACRONYMS

C++	C++ programming language
Ct	Current transformer
CT	Total life-cycle investment
DP	Total cost of depreciable property
EHV	Extra-high Voltage
FACTS	Flexible AC Transmission Systems
GUI	Graphical User Interface
HV	High Voltage
IC	Total cost due to load curtailment
ICES	Insulation Coordination Expert System
IEC	International Electrical Code
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
LP	Linear Programming
LV	Low Voltage
NEXPERT	Expert system programming shell
ND	Total cost of non-depreciable property
OOP	Object-oriented programming
PSIDE	Power System Intelligent Design Environment
Pt	Potential transformer
SIDE	Substation Intelligent Design Environment
SLD	Single-line Diagram
SVC	Static Var Compensator
SVS	Static Var System
TIDE	Transmission Intelligent Design Environment
TC	Transformer-Compensation group
Tcl/Tk	Graphical Interface Programming Environment
TCR	Thyristor Controlled Reactor
TRANSEPT	Expert system for the preliminary design of transmission line
TS	Total Evaluation Score
TSC	Thyristor Switched Capacitor
UPW	User Preference weight

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1. INTRODUCTION

1.1 Summary

The planning and design of electric power systems is a highly knowledge-intensive activity. This implies that design tasks rely heavily on a mixture of mathematical procedures and human expertise based on design experience. Although mathematical procedures are well established and easily accessible, human expertise is not so well defined or structured and, as such, not readily available to designers. This essential design expertise has furthermore eroded considerably over the years due to the recent slow growth of power systems and the retirement of experienced personnel. There is, therefore, a great need to structure, encapsulate, preserve and make such knowledge accessible to a broad audience. This thesis is an attempt to fulfil this need by proposing, developing and testing a general intelligent system for the design and planning of electric power systems.

The chapter begins by introducing the nature of design problems in general. Section 1.3 then focuses on more specific design problems in electric power systems. Since this area relies heavily on human expertise, the subject of artificial intelligence and particularly knowledge-based systems is then reviewed in section 1.4 with the intent of applying it to electric power system design problems, this being the main objective of this thesis. In the same section, two major knowledge-based modelling techniques are reviewed, namely, rule-based and object-oriented programming (OOP). In conjunction with the OOP discussion, the basic features of the C++ language are also outlined. Section 1.5 describes a general, milti-criteria approach for evaluation and ranking of design alternatives. Section 1.6 then provides a literature review of the various existing applications of intelligent systems to electric power system problems stressing planning and design. This is followed by a discussion motivating and justifying the work carried in this thesis, that is, the development of an integrated intelligent power system design tool. The chapter concludes with the claim of originality and the outline of the remaining chapters of the thesis.

1.2 The Nature of Design

Several definitions of design have been proposed in the literature. Thus, Asimow defines design as a "purposeful activity directed towards the goal of fulfilling human needs" [Asm62]. Archer describes design as a "goal-directed problem-solving activity which is mostly based on the decision-making process" [Bal93]. According to Simon, design could be seen as a "searching process whose objective is to find the physical or organizational schema which achieves certain goals while satisfying specified constraints" [Bal93]. A similar definition holds for the engineering design problem: "to devise, subject to certain problem solving constraints, a component, system or process to accomplish a specified task" [Dix66].

From this last definition it is possible to describe the engineering design process as consisting of the basic steps [Ata95-1] presented in Figure 1.1 and discussed below.

Define goals or objectives. Design is a goal-driven activity where the goals can usually be defined in terms of design functionality, level of design performance or user preferences. This is the most subjective step of the design process and has a major impact on all subsequent steps including the final design. Thus, the definition of the design goals is a crucial part of the overall design specifications. In engineering, such goals usually involve the design of a system or product which will perform

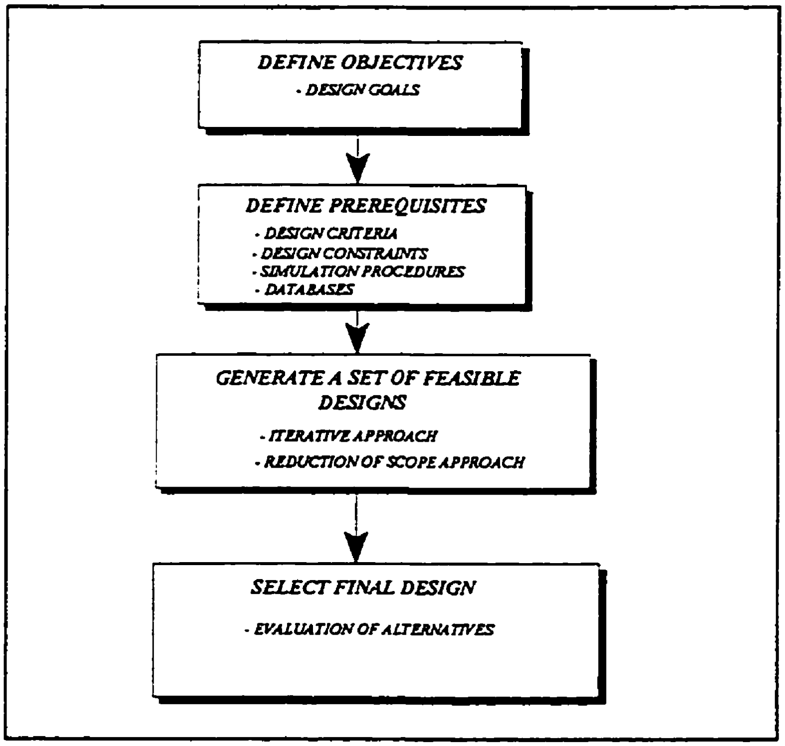

Figure 1.1: The Design Process.

certain tasks economically and reliably.

Define prerequisites. These are the necessary ingredients of any design consisting of criteria, constraints, simulation procedures and the relevant databases.

A design criterion is defined as a standard on which judgement or decision is based, thus, providing a rational basis for the choice of one alternative over another [McG93]. A constraint defines the range within which a design variable must lie for the final design to be acceptable (feasible). Heuristic or algorithmic simulation procedures must be executed in order to quantify those design variables which can only be determined by solving a complex set of relations (e.g. a set of non-linear equations). Finally, the databases contain all values of the input design parameters and the output design variables.

Generate a reduced set of feasible designs. Once the design objectives as well as the constraints, criteria and other specifications have been defined, the process of generating feasible designs can begin. This process is a combinatorial exercise involving an intelligent selection of a reduced set of potential design candidates. There are basically two main approaches to obtaining such a reduced set, namely, the *iterative approach* and the *scope reduction* approach. In the former, the design is improved through repeated modifications of design parameters and variables until all constraints are satisfied. This approach may involve a significant number of iterations and is convenient for systems consisting of a small number of sub-components. As for systems composed of a large number of elements, the scope reduction approach was found to be more suitable. Scope reduction is accomplished by applying a two-step filtering process whereby, initially, a limited number of alternatives is selected for each system sub-component. The second step filters out infeasible combinations of sub-components, leaving only a smaller set of feasible designs as candidates for the final design.

Select final design. In the last step of the design process, the reduced number of feasible designs is ranked according to a scalar measure obtained by assigning varying degrees of importance to criteria such as cost, reliability, flexibility and environmental impact. These degrees of importance or preference are chosen by the designer as part of the design specifications. The scalar measure used to rank the designs is determined by a technique called multi-criteria analysis [Mas88]. The final design selected is usually the highest ranked one, but human judgement may also influence the final choice.

1.3 Electric Power System Planning

The goal of power system planning is to conceive a reliable, flexible and economical power system. Its main activities may include the planning of a complete power system or of specific subsystems such as generation, interconnections, transmission and distribution networks, lines and substations. Performance requirements such as power flow and stability, insulation coordination, protection, control, grounding, reliability and cost evaluation must also be considered.

Two basic categories of knowledge can be identified in the power system planning process, namely, *the design knowledge* restricted to the specific design tasks (e.g. point-to-point transmission and substation design) and *global planning knowledge* mostly related to decisions of a broader nature such as whether or when to build new generation or an interconnection. *Design knowledge* modelling and processing are the main focus of this research and have been studied in great detail as opposed to *global planning knowledge* which has been treated at the conceptual level.

To describe the design knowledge in power systems, first the power system design process following the four general design steps described in the previous section is discussed in sub-section 1.3.1. The characteristics of power system design knowledge, including the structure of electrical power systems and their sub-components, are then addressed in sub-section 1.3.2.

1.3.1 Power System Design

1.3.1.1 Design Goals

In the design of electric power systems, the goal or objective is to generate a set of scenarios which satisfy the imposed design criteria and constraints while optimizing the overall performance with respect to four selected criteria, that is, cost, reliability, operational flexibility and impact on the environment. For example, in point-to-point transmission design [Lou93], the objective consists of designing a set of transmission systems characterized by the number and type of lines and substations, the amount and type of series and shunt compensation and the cost. Similarly, in substation design, the goal is to produce a set of alternatives characterized by selected arrangements of main substation groups such as high-voltage and low-voltage busbars, transformer sections and high-voltage and low-voltage line terminations, all of which satisfy the imposed operational constraints and meet the pre-defined user preferences.

1.3.1.2 Design Prerequisites

Power system design is subject to constraints over which one has little or no control such as *environmental* (rights-of-way, pollution level, climatic conditions), *financial* (ability to borrow and pay for investments) and *technological* (technical limits on equipment).

Criteria in power system design are technical requirements imposed by regulatory board or by the utility to ensure that a design meets certain standards such as insulation strength, short-circuit capacity, security and stability margins as well as audible noise and radio interference levels. In certain critical systems, a maximum permissible loss-of-load-expectation [End82] may also be a specified design criterion.

The simulation procedures implemented in power systems are purely algorithmic programs which are basically classified as follows: Steady-state (load flow, harmonics, corona, short circuits, audible noise and radio interference) and Transients (electro-mechanical and electro-magnetic). In addition, there exist simulation programs intended to determine reliability measures [End82], to evaluate costs, and to perform mechanical stress analysis [ABB88].

The databases in electric power systems consist of: electrical equipment, standards and statistics, input design specifications, as well as complete designs.

1.3.1.3 Generating Feasible Designs

In most power system design tasks, the objective is to build a complex system consisting of numerous sub-components. Moreover, the design tasks in the power system area are mainly characterized by sequential processing through a set of well-established design steps. Thus, the scope reduction approach described in section 1.2 is considered as particularly suitable for power system design. For example, in substation design, the main design steps are defined as follows [Ata95-2]: (i) select feasible single-line diagrams, (ii) perform required simulations (short-circuit and insulation coordination studies), (iii) select the substation electrical equipment. Furthermore, each of these three main steps consists of a sequence of its own design sub-steps. One example is the selection of the single-line diagram which is carried out in two sub-steps: selection of feasible configurations for each main part of the substation (busbars, transformer groups and line terminations) and their assembly into the complete substation. Another example of a typical power system design process is the point-to-point transmission design whose design steps are as follows: (i) select a set of possible transmission line types which are likely to be able to transmit the given power over the specified distance, (ii) generate a set of combinations of parallel lines and intermediate substations, (iii) select the type and estimated amount of compensation needed to meet the voltage, stability and reliability criteria.

1.3.1.4 Selecting Final Design

Once a set of feasible design alternatives has been generated, it remains to evaluate each alternative and to rank them according to a scalar evaluation index (based on the specified degrees of preference) as proposed in section 1.2. Detailed examples of this design step are also described in Chapter 3.

1.3.2 Power System Design Knowledge

"Knowledge is that representation of information that people tend to remember and manipulate in order to understand and solve problems" [Low95]. Design knowledge can be defined as the collection of facts, data, rules, guidelines, procedures and experiences associated with the design of a system. In this thesis, power system design knowledge is categorized according to: (1) Physical composition in terms of subcomponents, (2) Type of knowledge, (3) Knowledge distribution, (4) Knowledge processing. These are now discussed.

1.3.2.1 The Physical Composition of Power Systems

Electrical power systems are composed of subsystems which are in turn made up of their own components or subsystems. For example, a large power pool consists of several smaller interconnected subsystems which, in turn, contain their own substations, transmission lines and generation units. Furthermore, substations and transmission lines incorporate basic electrical equipment such as conductors, power transformers, circuit breakers, instrument transformers and busbars. The design process followed in this thesis takes full advantage of this natural structure of power systems. Thus, a complex system can be designed by putting together a set of progressively more complex subsystems.

1.3.2.2 Type of Knowledge

Three basic types of power system design knowledge can be identified: (i) *heuristic knowledge* based on human expertise (e.g. estimating the voltage level in transmission line design on the basis of the power flow and distance, selecting a substation busbar arrangement), (ii) *simulation procedures* (e.g. load flow and short-circuit algorithms) and (iii) *data* including system parameters, operating range of variables and equipment characteristics.

1.3.2.3 Knowledge Distribution

System subcomponents often contain some embedded knowledge about their own design which can be processed independently of the design of other subcomponents. This knowledge is referred to as *low-level knowledge*. On the other hand, *top-level* knowledge manages global decisions about the overall system structure and is usually processed during the first design steps. Top-level knowledge is associated with systems rather than with their subcomponents, whereas low-level knowledge rules perform more specific local tasks related to the specification of smaller system components.

As an example, in substation design the top-level knowledge is processed in order to select feasible single-line configurations of the substation, whereas the low-level knowledge encompasses rules and data related to the instantiation of the basic substation electrical equipment [Ata95-2].

1.3.2.4 Knowledge Processing

Most of the design tasks in power systems are carried out in a well-established sequence of steps rather than through iterative processes [Ata95-2]. This is particularly true when processing top-level knowledge where the decision variables are discrete (e.g. configuration of a single-line diagram, voltage level, type of compensation) and cannot be iteratively fine-tuned. This scope reduction approach is also commonly used in the processing of low-level knowledge in power system design.

An example of this type of low-level processing is the choice of the electrical equipment characteristics which must be made from a finite discrete set of manufacturer catalogue data.

A concrete illustration of the above considerations is the substation design process. The first step is to select feasible single-line diagram alternatives. The second is to perform the necessary simulations (short-circuit analysis, insulation coordination, load-flow) to obtain the parameters required at the third step where the selection of substation electrical equipment is carried out. The fourth step is the evaluation of design alternatives with respect to the specified performance criteria. A similar procedure holds for other typical design problems in power systems.

1.4 Artificial Intelligence and Intelligent Systems

The common link among the various definitions of artificial intelligence is that artificial intelligence emerged from numerous attempts to provide digital computers with reasoning capabilities similar to those of human beings [Win84]. Although developments in the computer industry have been extraordinary, the objective of making computers intelligent has proven to be more difficult than expected. One basic question which arises is: what degree of intelligence should computer based intelligent systems possess? Obviously, the main goal is *not* to eliminate human beings completely from decision making processes. Thus, one answer to the above question could be two-fold [Win84]:

(i) The first central goal of artificial intelligence is to make digital computers more useful by extending their area of application from solving purely numerical problems to tackling more heuristic, experience-based tasks, thus assisting human experts in performing more sophisticated activities. There are numerous such possible areas of application such as design, diagnosis, control and management in various domains (engineering, finance, medicine) which justify the impact of artificial intelligence on modern science and technology.

(ii) The second goal is motivated by the desire for a better understanding of the principles that make intelligence possible. This will require further research, particularly in the area of knowledge modelling and knowledge processing.

As far as human beings are concerned, there are several main characteristics which can be attributed to their intelligence. These include the ability to reason, the ability to acquire knowledge and the capability to apply the acquired knowledge. Accordingly, there are three basic activities which should be considered when developing an intelligent computer system: (i) the *knowledge acquisition*, (ii) the formation of the *knowledge model* and (iii) the development of the *reasoning* mechanism. The first activity consists of the following steps: identify domain knowledge sources (human experts, books, manuals, databases), acquire as much of the domain knowledge as possible from the identified sources and filter out the knowledge which is redundant or is not relevant. The second activity (knowledge modelling) is mostly related to the method of knowledge representation, while the third activity consists of analyzing different methods for knowledge processing, that is, to use knowledge to accomplish a desired task or to generate new knowledge.

There exist two main categories of intelligent systems distinguished principally by the scope of the knowledge addressed: expert systems and knowledge-based systems. Knowledge-based systems encompass broader knowledge related to several domains of expertise originating from many sources. On the other hand, expert systems are more focused on a specific area of expertise and are based on the knowledge and the experience of a limited number of sources or experts in the field.

A further subdivision of both categories of intelligent systems can be made depending on the manner in which the above-mentioned three basic knowledge activities (acquisition, modeling and reasoning) are accomplished. Two common approaches for knowledge modeling and processing can be identified, namely, the *rule-based* approach and the *object-oriented* approach. The following sub-sections outline the basic features of these two approaches to model and process the acquired domain knowledge. Special attention will be devoted to the object-oriented approach, this being the more convenient one for knowledge modelling and processing in power system design.

1.4.1 Rule-Based Systems

Rule-based systems are knowledge-based or expert systems where the knowledge is represented in terms of the following basic components [Hop93]:

1.4.1.1 Production Rules

Rules serve to represent the dynamic part of the domain knowledge, that is, knowledge about the actions which are taken and the conditions which have to be satisfied in order to carry out these actions and achieve the desired goals. Rules are usually represented in a natural form (for example an if-then structure) as opposed to the classical programming languages whose manner of representation is more abstract. The typical pattern of a rule consists of two parts, namely, the conditional part containing the conditions which have to be satisfied and the conclusion which describes the action to be taken when the conditions are met. There are two main types of rules: rules describing the domain knowledge and the so-called meta rules. The former are rules related to the application and are thus derived from different domain knowledge sources. The latter are not specifically concerned with the domain knowledge but are mostly employed to control the processing of the domain knowledge rules.

1.4.1.2 Facts or Assertions

Facts or assertions is information assumed to be true. In other words, facts can be thought of as rules whose conditional part is always satisfied. Facts could be constant parameters or relations comparing parameters such as inequalities [Coy90]. In rule-based systems, facts are used in the conditional parts of rules in order to generate new derived facts. Thus, one important characteristic of rule-based systems is their ability to extend the existing knowledge base by inferring new assertions.

1.4.1.3 Rule processing mechanism

In order to accomplish their task, rule-based systems have to process the domain knowledge by applying rules to a database of facts. This involves the following steps [Hop93]: (i) identify the proper set of rules which are closely related to the actual problem, (ii) determine which of the rules from the previously determined set are applicable (conflict set), (iii) perform a conflict analysis and select the rule to fire.

A typical rule-based system often consists of a database containing a large number of rules and assertions. Thus, the above-mentioned steps, which lead to the selection of the right rule to fire, may involve an extensive and difficult search procedure. Meta-rules can play an important role in accomplishing the rule selection task by introducing heuristics which can efficiently filter out a large number of non-applicable rules, thus significantly reducing the search space.

Obviously, the rule-selection is a rather complex procedure requiring a well-established strategy in order to be successful. Two important and frequently-used strategies are *forward and backward chaining*. The former is a data-driven process where the system starts with the given facts and continues to derive new facts through the rule-firing process. New and existing facts are then processed together, thus inferring more new conclusions until the goal is reached. This strategy is advantageous in terms of the production of new conclusions and solutions but it also has some disadvantages such as the possible waste of time when a feasible solution is not possible to find. Backward chaining is a goal-driven approach, that is, given an interpretation of a solution, the system tries to determine whether this solution is true. Thus, the system starts from the defined goal and tries to match it against one of the available facts or against the consequence inferred from the rules. In general, the forward chaining reasoning is more likely to succeed in systems with an abundant knowledge base (large number of facts) and a smaller number of possible goals (solutions) while the backward chaining strategy would be more favourable for systems with fewer facts and many possible goals [Coy90].

In conclusion, a typical rule-based system consists of two main parts: the knowledge databases containing domain knowledge expressed in terms of rules and facts as well as the so-called inference engine which encompasses the mechanisms for rule-firing control.

When power system design problems are considered, the use of the forward chaining strategy is preferable to backward chaining since these problems are usually characterized by a large number of known facts (design components) and a relatively small number of feasible solutions. One example of this would be a substation design where the designer has a large number of possible arrangements for different substation parts but where only a few combinations can constitute a feasible solution, thus restricting the solution (goal) space.

Although the forward-chaining strategy could be applied to power system design problems, the rule-based approach, in general, is not considered convenient for this kind of application. Instead, the object-oriented approach was found more advantageous for the reasons discussed below. The basic features of object-oriented intelligent systems are outlined in the following section.

1.4.2 Object-Oriented Systems

Several basic difficulties arise in the development and maintenance of large software applications:

(i) Even minor modifications may require extensive changes in the code because of strong links among the various procedures and variables. Maintenance requires detailed knowledge of each procedure and module.

(ii) Major extensions to the code such as the addition of a new module or a new interface may require a total redesign of the system.

The object-oriented approach offers various features which overcome the above mentioned difficulties. This approach is particularly convenient for modelling systems which consists of numerous smaller sub-components each of which represents an independent knowledge entity. Thus, the basic idea is to use *objects* as basic knowledge units in order to represent each system sub-component. In addition, these objects exchange information according to procedures embedded in their individual knowledge.

In object-oriented programming, programs are organized as cooperative collections of objects. Objects are defined as being instances of classes to which they belong, while a class could be defined as being a set of instances that share a common structure and a common behaviour [Boo91]. The real meaning of an object or of a class is explained more clearly in the following sub-sections where the most important characteristics of the object-oriented paradigm are discussed. These characteristics are the natural system representation, knowledge encapsulation, class hierarchy organization including the notions of inheritance and polymorphism, and system reusability.

1.4.2.1 The Natural System Representation

Objects and classes are basic concepts that are used to represent or model a complex system being studied. Obviously, there may exist many instances of the same class, all sharing the common class properties. In addition to these properties, a class can encompass additional knowledge related to the physical entity it tries to model. This natural knowledge could be used to assign values to the class properties, thus accomplishing the instantiation (creation) of a particular object. It could be also used to enable communication with other classes in the system, as well as to perform other tasks related to the class and its properties. This knowledge is preserved in special functions which are also class members and are called "class methods" in object-oriented terminology. The ability to preserve such dynamic type of knowledge, gives to a class a new quality called *knowledge encapsulation.* Knowledge encapsulation simply means that the complete information related to one physical entity is stored in one modelling unit, the class.

1.4.2.2 The Hierarchical Class Organization

The development of a complex object-oriented knowledge-based system may require the building of an extensive knowledge model consisting of numerous classes representing system components. These classes are organized in a hierarchical manner satisfying two basic kinds of relationships, namely, *inheritance* and *membership*. The former is an important mechanism reflecting the ability of one class (parent class) to define the common characteristics (properties) of several other classes (sub-classes) which *inherit* those common properties. In other words, the sub-classes could be thought of being a special kind of their parent classes having some particular characteristics in addition to the inherited common properties. Therefore, the mechanism of inheritance allows the definition of a new class of objects as a refinement of an existing class by simply specifying only the particular properties which characterize the new class while the common properties are inherited from the existing parent class.

Apart from the importance of inheritance, the mechanism of *membership* is also used very frequently when developing object-oriented class hierarchy models. Membership simply means that one class can have another class from the class hierarchy as its own member (property). As opposed to the notion of inheritance, the membership is characterized by *a part of* relationship between classes, that is, a class which is a member of another class is actually thought of as *a part of* that class and it does not inherit any of the properties from the class to which it belongs.

1.4.2.3 Polymorphism

In addition to the above discussed mechanisms of class inheritance and membership, there is another very important property of object-oriented systems which is directly associated with the class hierarchy organization, namely, the *polymorphism*. Polymorphism can be defined as the ability of two or more classes to respond to the same message, each in its own way [Boo91]. Thus, two distinct classes can possess methods which perform the same kind of task by implementing different knowledge rules. Therefore, the objects belonging to these classes will respond differently when accessed by such methods. Moreover, these classes can inherit common properties from their parent class, hence some of their methods may have a common set of knowledge rules which can also be inherited. Such kind of inheritance is accomplished by specifying a method belonging to the parent class which contains this common knowledge. In addition to the common knowledge, this method contains a call to another method belonging to the corresponding sub-classes. That method has the same name in both sub-classes, but it encompasses different, class-dependent knowledge thus eliciting a different response.

1.4.2.4 Reusability

Reusability is one of the key advantages of object-oriented programming because it significantly facilitates the development of new software applications. It can be defined as the flexibility to *reuse* previously existing developed components when building a new software system. To reuse means to take the whole existing components as they are and to include them in the new application without or with slight modifications. Another aspect of reusability is the ability to easily update the object-oriented software. Thus, in any class hierarchy tree, it is possible to add new sub-classes just by defining their particular properties while other common properties are automatically inherited from already developed appropriate parent classes.

The main steps of the object-oriented design process are outlined as follows:

Define the class hierarchy organization. The study of the system which is being modelled is conducted first in order to understand the system structure and to recognize the basic system sub-components as well as their inter-relationships. The information obtained from this study is used when defining system classes and when establishing the inheritance dependency of those classes. Basically, the class properties and the class hierarchy tree are defined at this step.

Define the class methods. The operations and tasks performed by methods and class constructors of each class are determined at this step. Thus, full knowledge encapsulation is accomplished by distributing the knowledge related to these tasks over the class methods. The notion of knowledge distribution is very important since it represents one of the basic advantages of object-oriented programming. Knowledge distribution implies that the total domain knowledge is subdivided into several knowledge groups. The advantage is that these groups do not need to interact too often during the knowledge processing but can be independently processed. Thus, the possibility to encounter conflicting situations is significantly diminished, particularly when it is possible to conceive a large number of knowledge groups, each containing a reduced amount of knowledge. As mentioned above, knowledge distribution is physically realized by means of class methods which *isolate* their pertinent knowledge from other classes.

Determine the sequence of class instantiation. In addition to the class hierarchy model, it is necessary to develop a knowledge processing scheme. Having defined the basic system ingredients, the purpose of this step is to instantiate these ingredients (classes) and put them together so as to create the outcome of the object-oriented design process, that is, an instance of the class modelling the final design. The order of instantiation, i.e., the sequence of messages passed (orders issued) to different classes is defined at this step.

Often, the process of governing the class instantiations does not represent a complicated control problem. Furthermore, since the possibility of conflicts has been reduced to a minimum in the process of instantiation, there is no need for any kind of inference engine to control the design process.

1.4.3 C++ As an Object-Oriented Development Tool

The growing interest in object-oriented programming has led to the development of several important programming languages and development tools such as: C++ [Pra91], SmallTalk [Parc89] and Eiffel [Mey92]. These languages support most of the object-oriented features described in section 1.4.2.

The C++ programming language has been chosen as the main development tool used to build prototypes in this research. The reasons which justify this choice can be summarized as follows:

• The object-oriented features such as knowledge encapsulation, inheritance and polymorphism are all provided in C++. Knowledge encapsulation is accomplished by means of *classes*, *structures* and *unions*. Structures and unions are well known methods of representing data in the C language, while classes pertain to the C++ language and embody all the necessary object-oriented programming characteristics. The *Class* is a C++ data structure composed of two parts, namely, the part containing definitions of class properties (attributes) and another part where class methods and operators are defined. Class properties and methods can be made inaccessible, accessible and partially accessible by other classes in the system by using private, public or protected declarations. Private declaration totally protects class properties, public declaration allows full access, while protected declaration permits access to the classes which maintain an inheritance relationship in the class hierarchy organization.

• Polymorphism is realized in C++ by means of operator and function overloading. As opposed to the C language, C++ allows the definition of different functions having the same name and even the same signature (list of variables which are passed to the function). In addition, the standard operators such as +,-,/ can be overloaded, thus giving them a different meaning depending on the application.

• In addition to the object-oriented features, the C++ language possesses a variety of powerful procedural capabilities. This is so, since C++ is actually a kind of a super-set with respect to the C having all facilities provided by the C language. This property facilitates the handling of various numerical and simulation problems and was found to be particularly advantageous in power system design.

• Most of the popular tools for building a GUI (Graphical User Interface) such as Xmotiff [Hel91] and Tcl/Tk [Ous93] are now programmed in C , thus requiring the C language as either the main development tool or the interfacing language to enable communication between the main application and the GUI. Since C++ encompasses all C language capabilities, any possible significant problems when connecting the main object-oriented application with GUI are thus avoided.

1.5 Multi-criteria Analysis

In this section, a general approach called *multi-criteria analysis* is presented for the evaluation and ranking of design alternatives [Mas88]. It is necessary to perform such evaluations at, not only the final design stage, but, also, during intermediate design stages when selecting basic components or sub-systems of the final design. In this thesis, design evaluation is based on four measures of performance or criteria, namely, cost, reliability, impact on the environment and operational flexibility[1]. Whereas cost and reliability can be more readily quantified, the last two criteria are more difficult to measure. Nevertheless, it is essential to consider somehow the last two criteria in the

[1] Of course, other criteria could be added to this list.

design since a power system should be easy to operate and should not affect in a negative manner its surroundings. Under multi-criteria analysis, such quantification is carried out through two basic steps:

(1) For each class of system components (e.g. the class of circuit-breakers or the class of busbar arrangements) a *relative score* is assigned to each of its members with respect to each of the criteria considered. These scores are usually expressed in dimensionless values from 1 to 10 and their purpose is to compare members from the *same class*. For example, among circuit-breakers the relative score with respect to reliability will assign a higher value to a SF_6 than to an air-blast or bulk-oil circuit-breaker since the latter two have been proven to be more likely to fail. On the other hand, the relative score with respect to the impact on the environment will assign the highest value to the air-blast breaker since this type has the least damaging potential effect on the environment. Sub-section 3.3.5.1 discusses these notions in more detail and provides numerical values. It is important to note that relative scores are defined in PSIDE through consultation with design experts and form part of the knowledge base. Thus, it is not possible for the user of PSIDE to alter these relative scores.

(2) In PSIDE, the user can however stress some criteria over others by specifying a set of percentage *user preference weights*. For example, some utilities may be forced to stress cost very heavily over any other consideration because of very limited resources. Alternatively, other utilities, may be required to stress more reliable designs with very low impact on the environment. Since the user preference weights must add up to 100%, this choice therefore entails a decreased emphasis on low cost designs.

Multi-criteria analysis is a decision making process where several distinct criteria are usually involved when performing a selection or evaluation of a design. There exist various approaches to solving the multi-criteria problem [Mas88] among which it is possible to distinguish very complex algorithms as well as relatively simple methods. The *weighted sum* approach [Mas88] presented here describes the above mentioned heuristic notions of relative scores and user preference weights. This approach was found satisfactory for implementation in power system planning and design. Its basic formula is as follows:

$$TS_i = \frac{1}{100} \sum_{k=1}^{4} RS_{ik} \quad UPW_k \tag{1.1}$$

where TS_i is the *total evaluation score* of design i (normalized from 1 to 10), UPWk is a user preference weight (in percent) with respect to criterion k and RS_k is the relative score (out of ten) of design i with respect to criterion k (see Table 3.8 for a number of examples).

The total evaluation scores are used when performing various design tasks, not only to select the final design, but also at intermediate stages, during the selection of sub-components or sub-systems.

1.6 Intelligent Systems in Electric Power Systems

The breakthrough of artificial intelligence in the electric power system area, which started in the mid eighties has resulted in the development of numerous expert system and knowledge-based system tools for solving various power system problems [Hun94]. Diverse methods of knowledge modelling and processing have been utilized such as object-oriented or rule-base approaches employing different types of inference mechanisms (forward chaining, backward chaining or hybrid). Accordingly, several

Table 1.1: Review of most important expert system applications in power systems [Hun94].

Area of Application	No. Public.	No. Tools	Knowledge Modeling	Development Tool
Alarm Processing	22	13	OP - 20%, RB - 55%, Oth. - 25%	C,Pr,F,K,O5,A
Control	14	-	-	-
Diagnostic	7	7	OP - 25%, RB - 40%, Oth. - 35%	Pr,L,C,C++,P
Distribution	27	27	OP - 30%, RB - 70%	P,L,C,F,K
Equipment Testing	7	-	-	-
Fault Analysis	44	19	OP - 22%, RB - 56%, Oth. - 22%	P,L,C,F,V
Monitoring	5	4	-	Pr,C,P
Maintenance	9	3	-	Pr, F
Network Switching	20	13	OP - 25%, RB - 75%	Pr, F, K
Operations	40	10	OP - 33%, RB - 50%, Oth. - 17%	P, L, C, P, F
Operator Training	10	3		
Planning	22	4	OP - 33%, RB - 67%	P, L, C, N
Protection	15	5	OP - 10%, RB - 90%	P, L, F
Reliability	7	-		
Restoration	27	10	OP - 20%, RB - 50%, Oth. - 30 %	Pr, L, C, C++, F
Security	25	13	OP - 15%, RB - 85%	Pr, L, C, F
Stability	16	1	-	N
Voltage Control	19	6	RB - 100%	F, OPS83

OP - Object-oriented systems	P - PASCAL	C - C language
RB - Rule-based systems	N - NEXPERT shell	C++ - C++ language
Pr - PROLOG	OPS83 - OPS83 shell	K - KDL language
F - FORTRAN	OP5 - OPS5 shell	A - ART hybrid shell
L - LISP	V - VL language	

types of development shells (Nexpert-Object, G2, Goldworks) and programming languages (Prolog, Lisp, C++) have been used to build commercial or prototype expert system applications. Table 1.1 provides a review of the work which has been done in the more important sectors of expert and knowledge-based system applications in electric power systems over the past decade [Hun94]. Eighteen major fields of application have been identified. A number of publications, application packages (tools, prototypes), types of development tools used (languages, shells) and methods for knowledge-modelling and processing implementations are summarized in Table 1.1 for each area of application [Hun94].

As far as power system planning and design activities are concerned, several areas of expertise have been explored, including global design problems such as distribution system design, transmission planning and design, substation design as well as those activities dealing with supporting design tasks such as protection and insulation coordination.

Expert and knowledge-based systems in the distribution design area include distribution protection systems [Tho94], operational planning [Tsa93] and distribution system modelling [Brau94, Wei95].

With respect to transmission planning and design, an important contribution has been made in the past seven years by the power group of McGill University. An ambitious program to develop a knowledge-based approach for the design of point-to-point transmission systems [Gal88, Ber89, Gal92, Lou93] has been undertaken and is almost completed. The first expert system tool in this program, called TRANSEPT, was developed for the design of point-to-point AC transmission networks [Gal88] using the LISP programming language. Subsequently DC TRANSEPT [Tru90] was later built to support DC transmission design leading to the integration of these two modules into one package TRANSEPT AC/DC [Lou93] realized by means of the NEXPERT-Object programming shell. In the course of these transmission design studies, the same group has carried out research in the area of supporting expert systems related to transmission design. For example, an expert system for insulation coordination [Gal90], also realised in the Lisp Goldworks environment, emerged as a result of this research.

Another important power system design activity, substation design, has not been approached from the perspective of intelligent systems. Some related contributions however exist and include an expert system for specifying the major substation components based on machine learning principles [Mah91-1, Mah91-2], as well as an expert system for designing power plant electrical auxiliary facilities [Jan87, Put88].

Protection system design is the area of expertise which is perhaps the most appropriate for the application of expert and knowledge-based systems. This is so since the design of protection systems represents an almost pure state-of-the-art process involving extensive heuristic knowledge based on human expertise. Most of the work in this area is associated with protection design of distribution system where typical activities are the location, selection and coordination of protective devices [Bro94, Tho94]. However, some work has been done in the field of expert system application in designing transmission line protection systems [Kaw95].

Finally, it is important to mention some contributions to the overall power system planning process involving long-term global planning activities such as the coordination among generation expansion, transmission and interconnection planning [Far88], [Shi93], [Ada94], [Tan].

1.7 Claim of Originality

The principal original contributions of this research are the following:

• The concept of an integrated knowledge-based power system design environment (PSIDE) encompassing the principal body of planning and design activities in electric power systems is proposed. This concept is then developed in substantial detail and a number of potential benefits are identified. These benefits include the preservation and consolidation of power system design knowledge and the development of automated tools emulating expert human reasoning useful for both training and for practical design purposes.

• A general object-oriented methodology is developed to realize the proposed planning and design model. The object-oriented strategy adopted herein takes full advantage of the natural structure and behavior of power systems as well as of the corresponding design methodologies. The general approach developed here is applicable to the vast majority of power system planning and design tasks such as substation design, insulation coordination, protection design as well as generation and transmission planning.

• In order to validate the proposed concept and its object-oriented realization, one of the major modules, namely substation design, is fully developed and tested. From this detailed example, design guidelines for the development of other design modules are extrapolated.

1.8 Outline of Thesis

This thesis is organized into five chapters. Chapter 1 is an extended introduction to power system planning, artificial intelligence techniques and object-oriented modeling including a literature review. Chapter 1 concludes with the claim of originality and the thesis outline.

Chapter 2 presents an integrated knowledge-based concept of power system planning and design, PSIDE. The general structure of a model and each of its pertinent modules (main and supporting expert systems and simulation tools) to realize this concept is described in detail. A general object-oriented methodology is developed and discussed for the realization of these modules. Finally, models for three typical power system design examples, namely, point-to-point transmission design, substation design and system protection design are presented.

Chapter 3 contains a full description of an advanced prototype for the substation design module, SIDE. An object-oriented representation of a substation emphasizing its subdivision into five main constituent groups is provided. The electrical equipment database organized in an hierarchical object-oriented manner is also discussed. Finally, a powerful graphical user interface is depicted.

Chapter 4 presents and discusses a set of substation design examples consisting of the graphical representation (single-line-diagram), tender document and design report as generated by the intelligent design tool developed here. The results of various simulations are also included in the design report including important evaluation indices. These indices are used to compare design alternatives and to select the most preferred final design. A full discussion regarding alternative design comparisons and the validation of SIDE is also found in this chapter.

Chapter 5 summarizes the important points of this research in the form of conclusions. Future objectives are also outlined.

2. AN INTELLIGENT POWER SYSTEM DESIGN ENVIRONMENT

2.1 Summary

For the past seven years, the Power Engineering group of McGill University has been engaged in a program to develop a knowledge-based or intelligent approach [Gal88, Gal92, Lou93, Ber89,Ata95-1, Gal90,Bel96-1,Bel96-2,Ata94] for the planning of electric power systems [Epri89,Ata95-1,Wood82]. This effort was motivated, to a large degree, by the fact that power system design knowledge is widely scattered and in danger of erosion due to the retirement of human experts and an over-emphasis by the power industry on commercial rather than technical considerations. The intelligent approach is an attempt to identify the wide body of power system planning and design knowledge, to gather it and to structure it into one easily accessible source for purposes of preservation, consolidation and training.

The main power system planning activities considered by this approach include the design of a complete power system or of specific subsystems or components such as generation, interconnections, transmission and distribution networks, lines and substations.

As mentioned in the Introduction, two basic categories of knowledge can be identified in the power system planning process, namely, *technical design knowledge* restricted to specific design tasks (design of a particular component such as a point-to-point transmission network, a substation, etc.) and *global planning knowledge* mostly related to the management of the overall process (e.g., a decision to build new generation or to opt for an interconnection). This thesis emphasizes technical design knowledge modelling and processing rather than global planning knowledge which is only briefly discussed.

This chapter, first proposes an intelligent design environment (PSIDE, Power System Intelligent Design Environment) for the overall power system planning and design process [Ata95-1]. In order to develop the proposed design environment, a general object-oriented methodology is described. Finally, some examples of typical design tasks belonging to PSIDE such as point-to-point transmission, insulation coordination and protection design are briefly discussed to illustrate this general methodology. In addition, Chapter 3 describes a fully-developed object-oriented module of PSIDE for substation design to practically validate the proposed design environment and methodology.

2.2 Introduction to the Intelligent Design Environment

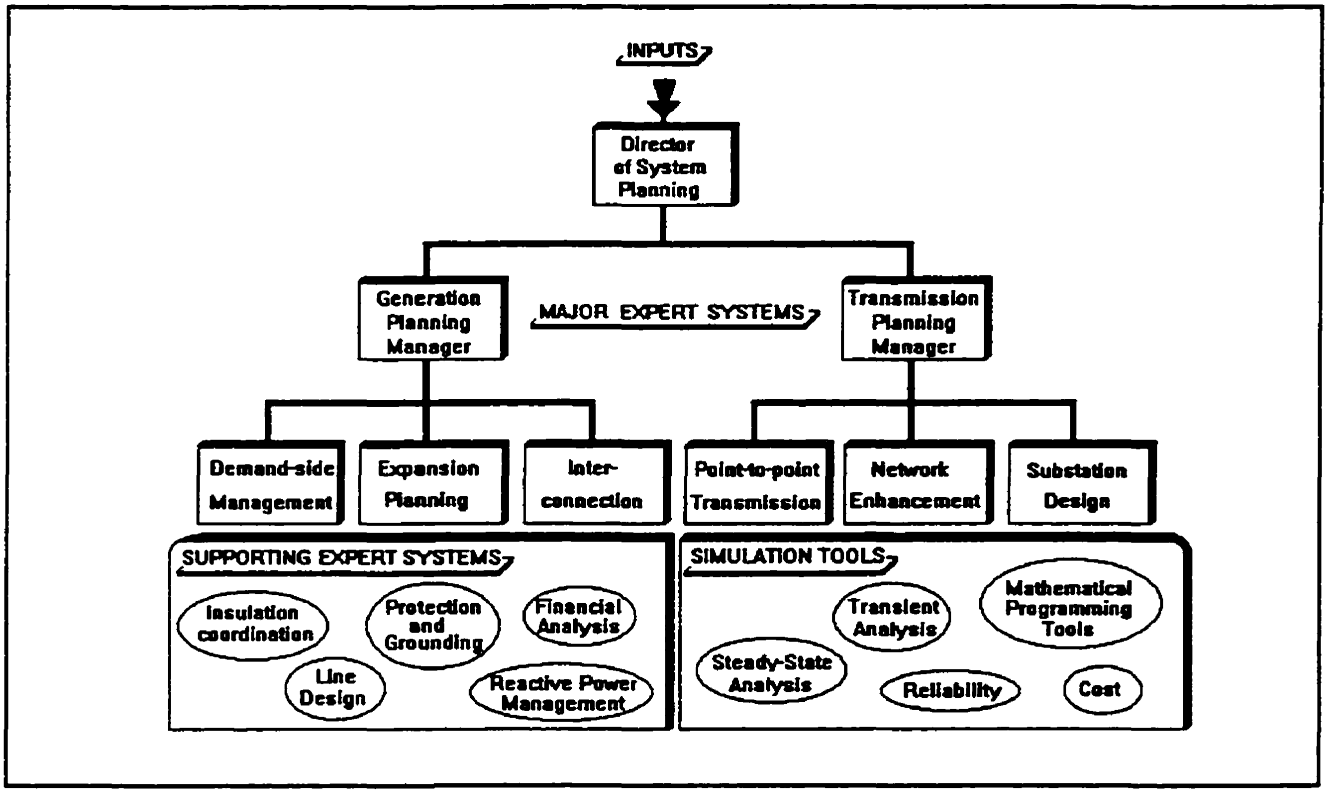

Figure 2.1: The power system intelligent design environment (PSIDE).

Figure 2.1 describes the proposed knowledge-based model of the power system planning process [Ata95-1]. It encompasses four distinct levels, namely, *Inputs, Major Expert Systems, Supporting Expert Systems* and *Simulation Tools*. These levels represent the major activities normally associated with system planning in a power utility. A number of databases not shown in the Figure also exists containing information about equipment, available designs, statistics and design norms and standards.

The contents of the various components of Figure 2.1 and their inter-relation are now discussed in the following sub-sections.

2.2.1 Inputs

The *Inputs* are the driving forces which set the planning activity in motion. These are: *System Deficiencies*, *Load Growth*, *Change of Design Criteria*, and *New Technologies*. The processing of such inputs requires a continuous effort since they are subject to frequent changes. These are now elaborated upon.

2.2.1.1 System Deficiencies

Deficiencies in the system performance such as over or undervoltages, excessive frequency fluctuations, equipment overloading or frequent power interruptions are generally the result of inadequate design or operating strategies or lack of maintenance. However, the root cause of most deficiencies is a system that is not sufficiently robust. This type of input, would typically trigger a reasoning process involving high and low level activities in several modules. For example, a line which repeatedly overloads, would cause the Director of Planning module to invoke the module Transmission Planning Manager which, in turn, would request a corrective measure from the Network Enhancement module. Possible corrective measures are: building a new transmission line, adding a FACTS device or modifying the power flow control scheme. The final choice of which corrective action to implement is made by the Director of Planning module based on technical, cost and other considerations.

2.2.1.2 Load Growth

Load forecasting over a horizon of five to twenty years is another important input to the planning process. PSIDE must accomodate the vagaries of load growth and be flexible enough in order to accelerate or slow down the system expansion accordingly. This input is processed by the Director of System Planning and may be transmitted to both the Generation and Transmission Planning Managers, although the former is the more likely module to be invoked. The Generation Planner must study and recommend choices from among the Demand-Side Management, Generation Expansion or Interconnection modules.

2.2.1.3 Changes in Design Criteria

Changes in design criteria are often an efficient and convenient way of improving the system robustness or they may be imposed if a utility needs to interconnect to another system with stricter design criteria. Such changes include raising the severity of the fault criterion (e.g. from single-phase to three-phase fault), decreasing the fault criterion duration time, applying stricter control of overvoltages, going to higher insulation levels and operating margins of security, or augmenting the generation and transmission reserves. Any of these changes would trigger planning activities involving mainly the Transmission Planning Manager which has access to a variety of possible solutions within its knowledge base.

2.2.1.4 New Technologies

New technologies such as electronic power flow control devices [Gyu94] and demand-side management strategies [Tal86] can also be considered as inputs to the planning process in order to examine their potential impact on the system design. New technologies should be used to take full advantage of the capabilities of the existing power system investments such as utilizing the existing transmission network to its maximum.

2.2.2 Major Expert Systems

These expert systems model knowledge at the highest level of system planning in PSIDE. Major expert systems include the Planning Director, the Generation Planning Manager and the Transmission Planning Manager which model long-term global planning activities. Other major expert systems which characterize more specific technical design tasks are: Point-to-Point Transmission, Substation Design, Network Enhancement, Demand-Side Management, Expansion Planning and Interconnection. In a manner analogous to the actual organization of the planning activities in a power utility, at the highest level, a Director of System Planning module defines, on the basis of the triggering inputs, the planning objectives, the scope of the problem and delegates appropriate responsibilities to its subordinate modules, the Generation Planning Manager and the Transmission Planning Manager. These, in turn, have access to other major and supporting expert systems as well as to simulation tools. Subsection 2.2.5 gives an example of how the system planning process is managed at each level.

2.2.2.1 Generation Planning Manager

This expert system is intended to direct the generation planning activities associated with the development of a power system. Such activities include:

- Generation Expansion Planning. This expert system module consists of the inventory of needs and natural resources available, the grading of such resources, the types or mix of generation and of course, the costs involved. This module makes use of both heuristic methods and mathematical programming tools [Wood82, Wal85].

- Demand-side Management Planning. This module considers potential demand-side management schemes (e.g. time-of-day tariffs, direct load control, conservation incentives) as alternatives or supplements to the generation expansion plans [Sul77, End82, Wood82]. Demand-side management can also affect the transmission planning process by modifying load patterns in areas where the transmission capacity is stressed.

- Interconnection Planning. This expert system module is presently being developed [McG96-2] to evaluate the technical and economical implications of interconnecting two or more power systems. Interconnections have a strong impact on generation expansion planning since they can reduce the required generation reserves. As with demand-side management, interconnections also have an impact on transmission planning.

2.2.2.2 Transmission Planning Manager

This expert system is intended to direct the transmission planning activities associated with the development of a power system. Such activities include:

- Point-to-Point Transmission Design. One version of this expert system module has already been developed [Gal88,Gal92,Lou93,Ber89]. Its purpose is the preliminary design of a transmission corridor connecting two points in an existing network. This design is intended to transmit a given amount of power over the given length of the corridor. Both AC and DC transmission alternatives are considered together with a reliability and cost evaluation of the systems designed. More details on this module are provided in section 2.3.

- Network Enhancements. This expert system module is still in the conceptual stage but it is intended to design enhancements of a general nature to an existing transmission network beyond a simple point-to-point transmission system. These enhancements are created at the command of the Transmission System Manager. An example of how the module Network Enhancements functions is as follows :

  Suppose that the Transmission Manager has instructions from the Planning Director to change the stability criterion to a stricter level. The Transmission Manager has within its knowledge base instructions to invoke Network Enhancements for this type of request. In turn, the Network Enhancements module has within its knowledge base a number of alternative means to solve this problem: (a) Addition of faster excitation systems to existing generation units.

(b) Addition of series compensation to a set of existing lines where both the amount and location of the series compensation is to be determined. (c) Addition of static VAr compensation to a set of existing buses where both the amount and location of the compensation is to be determined. (d) Building of one or more additional lines. The module Network Enhancements determines a wide spectrum of feasible alternatives by executing steady-state and transient simulations as well as cost and reliability evaluations. From a study of these alternatives, this module recommends a reduced set of design alternatives to the Transmission Manager who, in turn, based on these studies but also on other non-technical considerations, recommends a final design to the Planning Director.

• Substation Design. This expert system module is the most ambitious and comprehensive so far developed [Ata94,Ata95-2]. It generates substation design alternatives evaluated in terms of cost and reliability through a set of rules, procedures and design criteria used by human experts. This application is discussed in extensive detail in Chapter 3 of this thesis.

2.2.3 Supporting Expert Systems

These modules are dedicated to more specific tasks and are called upon by the major expert systems to supply a particular ingredient to the overall design. The supporting expert systems are *Insulation Coordination, Line Design, System Protection and Grounding* and *Financial Analysis*. These systems are now briefly discussed in order.

2.2.3.1 Insulation Coordination

This expert system module ensures that the power system design will withstand adverse service conditions with an acceptable degree of reliability [Gal90,IEC71]. The knowledge base includes the system overvoltages and the response of the insulation to these voltage stresses. The coordination exercise consists of the selection of the electric strength of the insulation taking into account the protective margins provided by surge arresters for non-self-restoring insulation and by an acceptable risk of failure for self-restoring insulation. The output of this module consists of such items as the switching and lightning impulse withstand voltages of major equipment and the insulation dimensions of the towers and substation buses. This module can be invoked by the modules Substation Design and Line Design. An object-oriented model for insulation coordination is presented in more detail in Section 2.3.

2.2.3.2 Line Design

This expert system provides a methodology for the structural design of a transmission line [Epri82] and for estimating its cost [Epri82]. This is an essential ingredient in transmission planning, especially for long distances where line costs can reach 75 percent of the total cost of a transmission system (the remaining being the cost of the substations). This expert system covers both AC and DC transmission lines at all voltage levels. It takes into account varying terrain conditions and environmental constraints, reflected in the type of towers that are most appropriate. The main consideration in the design of a line is the choice of conductor based on corona effects for high-voltage lines and on the overall costs, including the cost of losses. Line Design is invoked by the Point-to-Point Transmission Design module.

2.2.3.3 System Protection and Grounding

This module will deal with the choice of protection and grounding systems for faults, overloads, undervoltage, underfrequency and system stability as well as special protective devices for extreme contingencies. System Protection and Grounding is invoked by the modules Network Enhancements and Substation Design.

2.2.3.4 Financial Analysis

The aim of this module is to generate a set of financial plans for a given project. These plans will include factors such as: sources and schemes of financing a project, interest rates, cost and revenue forecasts and payback period. This module is normally invoked by the Director of System Planning or by the Generation and Transmission Planning.

2.2.4 Simulation Tools

These consist of purely algorithmic simulation programs called upon by the major or supporting expert systems. They are basically classified as follows: Steady-state simulation tools (load flow, harmonics, corona, short-circuits, audio and radio interference) and Transient simulation tools (electro-mechanical and electro-magnetic). Other important simulation programs determine probabilistic adequacy and security measures, evaluate costs and perform mechanical stress analysis. Simulations are called upon by the majority of the design modules described above. There are three main reasons for invoking such simulation tools: (a) to verify that the choice of design parameters based on heuristic rules meets the criteria and constraints, (b) to fine-tune an existing feasible design over a range of design parameters, (c) to calculate certain performance indices (e.g. LOLE, cost) in order to limit the number of feasible designs.

2.2.5 Management of the Overall Power System Planning Process

This section describes how PSIDE manages the planning process.

Each module of the model shown in Figure 2.1 possesses its own level of expertise and decision-making capability. The Director of System Planning module contains knowledge about how to respond to the various possible inputs. It determines whether to invoke the Transmission Planning or Generation Planning or both modules. Each subordinate module returns (after invoking a sequence of other modules) a reduced set of alternative designs to the Director who decides on a preferred solution. In the example of the previous Section, where the input was a change in the stability criterion, the Director 's choice was restricted to only a transmission enhancement solution. Another example of this decision process is where the input is a Network Deficiency such as a transmission bottleneck. In this case, the Director knows that this problem could be potentially solved by either enhancing the network or by augmenting generation capacity. Both modules are therefore invoked. Possible Generation Planning solutions may include adding new generation, building a new interconnection or by means of demand-side management while alternative Transmission Planning solutions may include new lines or the use of FACTS devices. The modules Transmission and Generation Planning, in arriving at a set of recommended designs, invoke the various supporting expert systems and simulation tools. The final choice of the Director will be primarily based on a balance among cost, environmental impact, flexibility and reliability comparisons. A specific example of this type of trade-off will be given in Chapter 4.

2.3 Object-Oriented Approach to PSIDE: Typical Power System Design Tasks

The object-oriented model of PSIDE consists of (i) an *equipment* database, (ii) several class hierarchies of *composite-parts*, (iii) a class of *simulation* tools and (iv) a *design-session* class.

(i) The *equipment* database is an object-oriented database incorporating all basic equipment (including their properties) used by the various power system design modules.

(ii) The *composite-parts* class hierarchies model the various sub-systems of the final system being designed. Such a class hierarchy must be created for each different type of design problem. It must contain models of all likely implementable sub-systems. For example, in substation design, there exists several class hierarchies modelling the constituent parts of the station such as busbar arrangements (e.g. double-bus, ring, breaker-and-a-half) or transformer groups. The objects in a composite-parts class are instantiated during the design process from the more basic objects belonging to the equipment databases. This instantiation is carried out by methods encapsulated within the class definitions. For example, a typical busbar arrangement is made-up of busbar conductors, disconnectors and circuit-breakers from the electrical equipment database class hierarchy.

(iii) The class of *simulation* tools contains mostly algorithmic procedures such as load forecasting, load flow, transient stability, short-circuit analysis, cost and reliability analysis. These procedures can be used by any of the design modules.

(iv) The *design-session* class contains the complete information related to a design session including a set of all design alternatives as well as intermediate results obtained during the knowledge processing (simulations, processing of heuristic rules and explanations).

Section 2.3.1 below discusses in considerable detail the object-oriented equipment database used by all power system design modules. The remaining three elements in the object-oriented model of PSIDE (composite-parts, simulation tools, design session) are discussed in more detail in sections 2.3.2 to 2.3.4 through specific power system design tasks.

2.3.1 The Object-Oriented Equipment Database

The equipment database contains the most basic elements of electric power systems. These elements are assembled to make up more complex configurations (substations, transmission systems) which are further grouped to constitute entire power networks. The fact that the same electrical equipment are used by various power system design activities makes it necessary to build a general equipment database [Ata95-2] (Figure 2.2). For example, electrical conductors and circuit-breakers must be accessed when designing substations as well as transmission networks.

There exist different concepts which could be adopted when developing a database system, the main ones being relational and object-oriented databases [Kim90, Del92]. In the case of electrical equipment, the object-oriented approach was selected for its many useful features as discussed below.

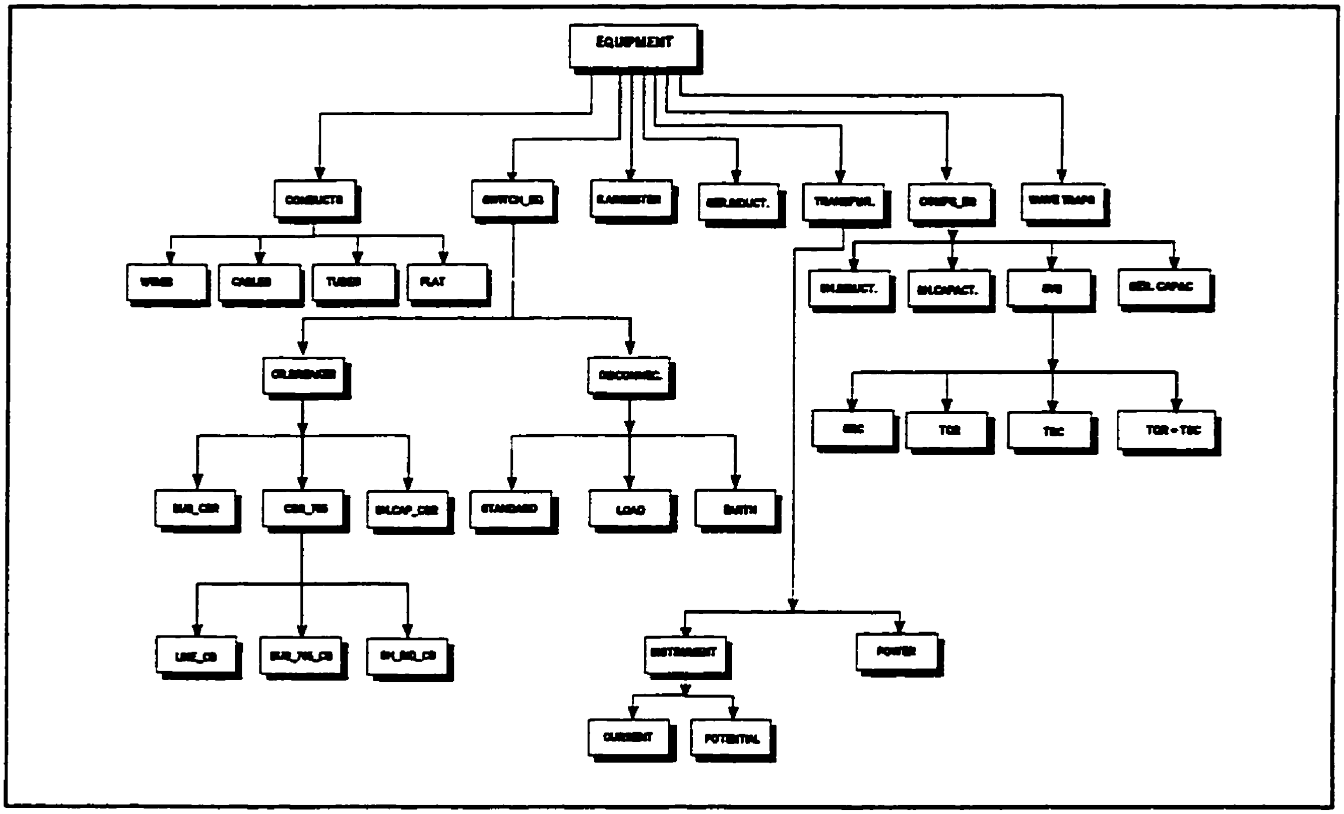

Figure 2.2: The electrical equipment database.

Hierarchical class structure. Each piece of electrical equipment is characterized by a set of electrical characteristics (nominal voltage and current, short-circuit level, insulation level, etc.) plus other non-electrical properties (reliability, cost, dimensions). Since some of these characteristics are common to several electrical apparatus, grouping them into larger structures (classes) is convenient. These larger classes contain common properties (e.g. nominal voltage) which are inherited by their sub-classes which may also have their own sub-classes and so on, thus forming the so-called class hierarchy scheme. Where electrical equipment is concerned, the top class called "Equipment" contains common properties pertinent to every piece of equipment such as: rated voltage, insulation level, cost, reliability indices and physical dimensions representing the highest level of generality. The sub-classes are organized according to the more specific properties presented in Figure 2.2 and described as follows:

• Switching equipment. Circuit-breakers and disconnectors are basic sub-classes of this major class. Since this type of equipment is usually connected in series, their common properties are nominal and short-circuit currents as well as longitudinal and phase-to-ground insulation levels. Further sub-division is based on the fact that there exist several different types of circuit-breakers and disconnectors. EHV circuit breakers, for example, can be divided into those used for switching lines, buses or shunt reactors. Obviously, typical properties for all types of circuit-breakers such as interrupting capacity are also properties of the top breaker class (class "Circuit-Breaker" in Figure 2.2) while more specific characteristics (e.g. closing resistor in EHV breakers) are contained in lower sub-classes. Similarly, disconnectors are sub-divided into standard disconnectors, load disconnectors and grounding switches.

• Transformers. According to their role in the power system, transformers can be classified into two main categories: instrument and power transformers. Furthermore, current and potential transformers are classified as sub-classes of instrument transformers. The corresponding class hierarchy organization is displayed in Figure 2.2. The common properties which are inherited by every transformer are, for example, insulation levels and power ratings. Typical properties of instrument transformers are voltage/current errors while power transformers would have the voltage and power ratings as well as impedances as particular characteristics.

• Compensation equipment. The main classification of compensation equipment is according to the way this equipment is connected (shunt or series). Thus, shunt reactors and shunt capacitors as well as static var systems are classified as sub-classes of the class "Shunt" (Figure 2.2) while series capacitors and phase-shifters belong to the class "Series". Both classes ("Shunt" and "Series") are structured under their parent class "Compensation".

• Electrical conductors. The principal sub-classes here model stranded-wires, cables, tubular and flat rigid conductors. They all have current-related common properties such as current-carrying capacity and short-circuit withstand capabilities but differ in their mechanical characteristics (type of material, shape).

• Protection equipment. Two different kinds of protection equipment are distinguished: surge arresters (protection against overvoltages) and relaying equipment (protection against faults). These have very few common characteristics and are classified under the same class only because of their common purpose - to ensure protection of the system and its components.

• Communication equipment. At present, only wave traps [ABB88] are considered as a sub-class of the "communication equipment" class.

Knowledge encapsulation. The above-mentioned properties of electrical equipment represent only a part of the knowledge preserved inside any of the equipment classes. A more important part is the knowledge which is processed in order to assign values to these properties (instantiation). This knowledge, usually represented in terms of well-structured heuristic rules or numerical procedures, is embedded in class methods and hence preserved inside the class itself. This property of storing the complete information about one entity in one place (inside one class) is called knowledge encapsulation and represents one of the basic characteristics of object-oriented database systems [Kim90,Del92,Cox86]. In the electrical equipment database one example of knowledge encapsulation would be the instantiation of EHV-bus circuit-breakers. The knowledge related to the selection of breaker type (SF6, air-blast, minimum-oil) is located in methods which perform type selection while other methods verify the breaker current and insulation characteristics to meet the design specifications.

Polymorphism and reusability. In addition to the inheritance of common properties, common class methods, that is , methods which perform the same type of tasks for different classes may also be inherited. This property of inheriting common methods (or parts of these methods) is called polymorphism [Cox86]. One example where polymorphism is valuable in the management of the equipment database is in the addition or deletion of circuit-breakers. The method that performs this task is only slightly different from the case where any other piece of equipment is deleted or added. The common part of this add/delete procedure is therefore a method inherited from the parent classes "Equipment" and "Switching Equipment" (Figure 2.2). Other examples of polymorphism in design will be discussed later in this thesis.

Another important characteristic of object-oriented databases is reusability. When introducing a new class of electrical equipment to the database, one needs to specify its location in the existing class hierarchy. This usually implies that the new class will inherit a number of properties from its parent classes. In this sense, the properties and code inherited are reused by the new class. An example of this type of reusability is the addition of a totally new class of compensation equipment such as FACTS [Gal96, Gri96, McG96-1] to the database.

The detailed description of the electrical equipment database including a more detailed description of each electrical apparatus is provided in Chapter 3 (design of electrical substation).

2.3.2 Point-to-Point Transmission Design

This section gives an overview of the point-to-point transmission design module in the preliminary design of a transmission corridor connecting two points in an existing power network [Gal88]. This module is part of a doctoral thesis [Lou96] and only its highlights are described here in the context of the overall design tool PSIDE. Given the amount of power to be transmitted and the length of the corridor, this knowledge-based module generates a set of feasible point-to-point designs evaluated with respect to four basic criteria of performance, namely cost, reliability, impact on the environment and operational flexibility. Both AC and DC design alternatives are considered [Ber89].

The point-to-point transmission design is a knowledge-intensive process relying on broad heuristic engineering expertise as well as complex simulation procedures. One expert system for the preliminary design of point-to-point transmission has already been developed [Gal88,Gal92,Lou93, Lou96, Ber89] with the acronym TIDE (Transmission Intelligent Design Environment). This expert system was based on a model using a forward-chaining rule-based paradigm, having an object/class structure as well as links to external simulation procedures (load flow, stability and overvoltage analysis).

In order to incorporate TIDE into the integrated power system design environment proposed in this thesis (Section 2.2), TIDE must be modified to follow the object-oriented approach outlined in the previous sub-sections. Thus, the concepts of knowledge distribution including the identification of *top-level* and *low-level* knowledge [Ata95-2] are introduced in the following subsections for point-to-point transmission design.

2.3.2.1 The Object-oriented Model of TIDE

As shown in Figures 2.3 and 2.4, two basic class structures constitute the object-oriented model of the proposed point-to-point transmission design module, namely, the "Design-session" class and the "Composite-parts" classes.

The "Design_session" is a class whose instance contains the entire information related to a design session. This includes, not only information about the final design alternatives but also intermediate information on how these alternatives have been generated during the design process. Thus, as depicted in Figure 2.3, the members of the "Design-session" class are the following classes: "Heuristics", "Simulations", "Transmission" and "Evaluation". The class "Heuristics" contains data related to the processing of heuristic rules (preselected voltage levels, number of substations, basic line-conductor parameters, selected number of circuits, estimated amount of shunt and series compensation). The class "Simulations" contains results obtained from simulations (e.g., fine-tuned values of initially estimated amounts of compensation) while the class "Transmission" preserves a set of complete design alternatives. Finally, the class "Evaluation" contains information regarding the evaluation of the resulting design alternatives with respect to the four criteria of performance, namely, reliability, cost, operational flexibility and impact on the environment.

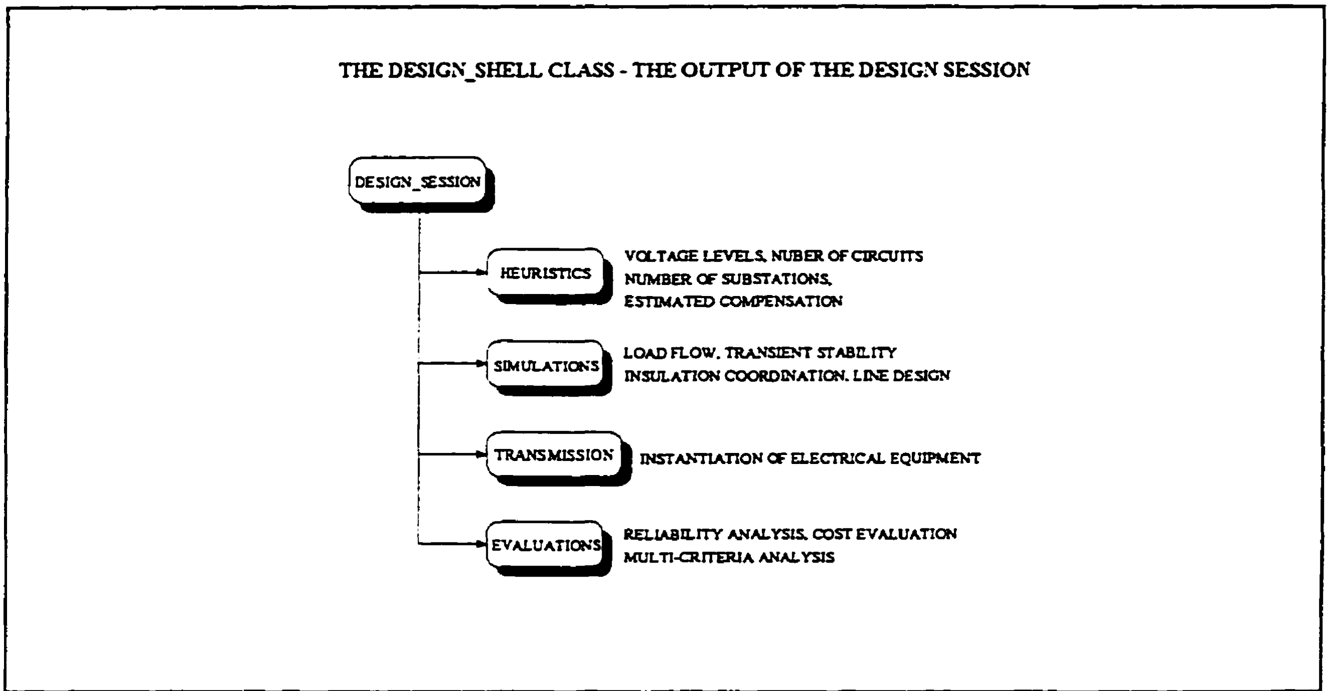

Figure 2.3: The design-session class of TIDE.

In this particular case of point-to-point transmission design, the class hierarchy “Composite-parts” defines one type of composite part, namely, "Transmission_types" (Figure 2.4). This class models two basic types of transmission systems, that is, AC and DC transmission. As presented in Figure 2.4, the "AC_transmission" class consists of two classes: "BusAC" and "LineAC". The class "BusAC" encompasses knowledge related to the terminal buses of the AC line. This knowledge basically refers to the load , generation and shunt compensation connected to each bus. Similarly, the class "LineAC" describing AC transmission lines is composed of three classes, namely, “Conductors”, “Compensation” and “Substations” as seen in Figure 2.4. These three classes are in turn sub-classes of other hierarchies not shown in the Figure.

Moreover, as shown in Figure 2.4, the class tree is further expanded to include basic electrical equipment. For example, the class "Series_compensation" may have different possible instances such as series-capacitor or phase-shifter [Ira94], whereas the class "Shunt_compensation" may be instantiated as "Shunt_capacitor" or "Static_var_system" which in turn can assume several forms [Sta86].

The class "DC_transmission" is also composed of classes similar to those of the AC case, namely, "BusDC" and "LineDC". The class "BusDC" consists of classes modelling its load and generation as well as a third class named "Terminal-eq" describing the conversion/inversion apparatus. The corresponding class "LineDC" is composed of only one class modelling the line conductor. It is important to note that both systems (AC and DC) inherit common properties from the top class ("Transmission_types") such as insulation and tower characteristics [Epri82, IEC71].

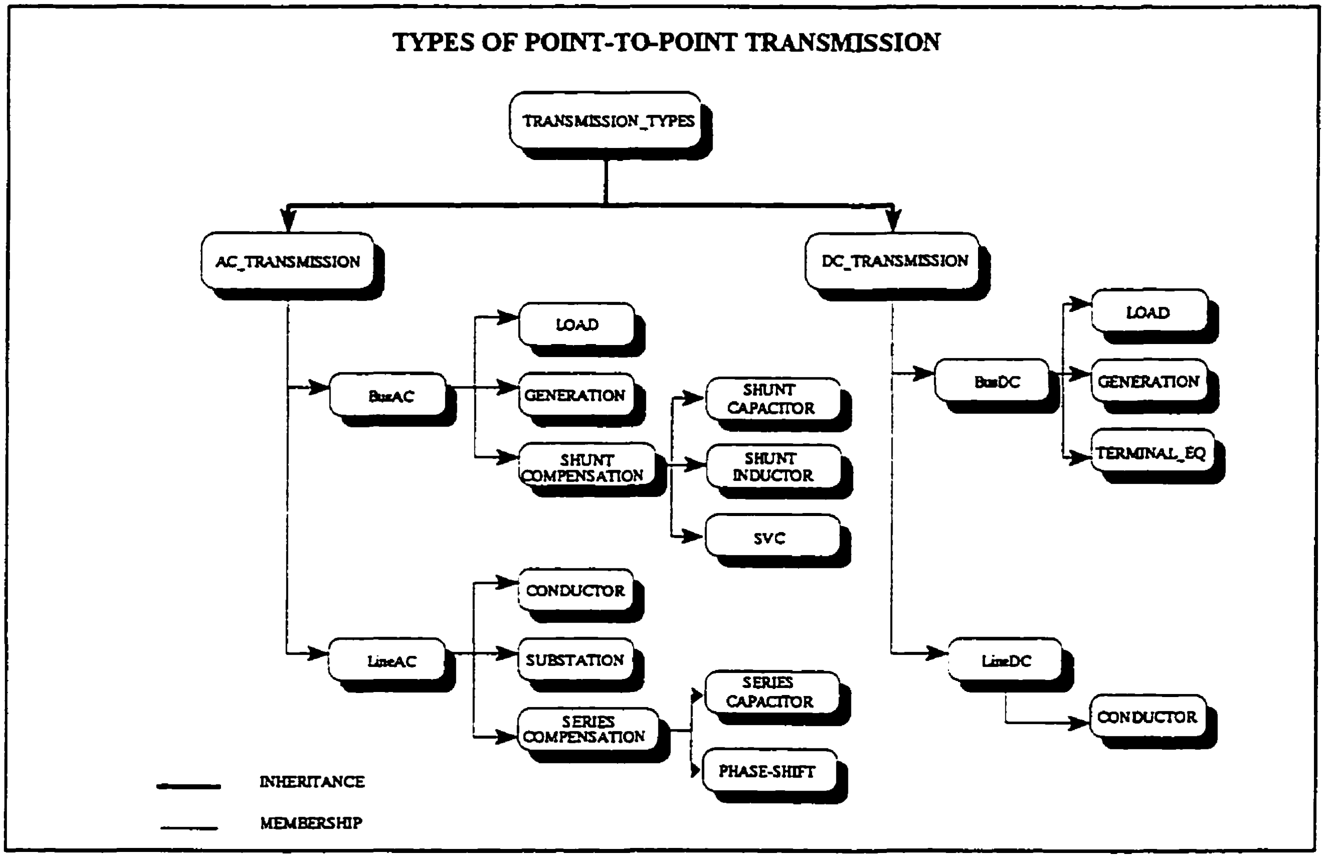

Figure 2.4: Transmission types.

2.3.2.1.1 Knowledge Processing in TIDE

Domain knowledge is processed in order to complete the properties of the above described classes, thus creating the corresponding class instances. As outlined in section 2.2, two types of knowledge distribution are considered: (i) the distribution according to the scope of processing, i.e., global (top level) versus local (low level) knowledge, and (ii) knowledge distribution over various classes (encapsulation). The following sub-sections describe knowledge distribution in point-to-point transmission design.

Top-level knowledge. Heuristic knowledge, which is processed at the first stage of the design to instantiate the class "Heuristic", constitutes top-level knowledge. The following is a sequence of design steps required to provide an instance of the class "Heuristic":

"AC_transmission" class:

- Given the amount of power and the distance, the heuristic expertise estimates the possible voltage levels from a set of rated voltages.
- A nominal number of intermediate substations is estimated.
- Nominal line parameters (impedances, admittances) are determined based on the estimated voltage level and power rating.
- The number of circuits is estimated.
- The amounts of series and shunt compensation are estimated.

These steps define the general characteristics of the transmission system. Simulations are then executed to fine-tune the nominal characteristics found above to meet the specified design criteria.

"DC_transmission" class:

- The possible voltage levels are estimated based on power and distance.
- The basic line and terminal substation parameters are selected.
- The minimum number of bipolar lines are estimated.

Low-level knowledge. Once the top-level knowledge processing has been accomplished, the selection of the basic components (electrical equipment) naturally follows. The electrical equipment considered when designing a point-to-point transmission system can be summarized as follows: transformers, line conductors, static var compensators, shunt reactors, shunt capacitors, series capacitors, phase shifters and substation equipment. The object-oriented equipment database described in the previous section contains models and knowledge related to this type of electrical equipment. The knowledge which instantiates a particular electrical apparatus is therefore contained in database class methods and is called low-level knowledge. This knowledge is used to instantiate the class "Transmission" which, in turn, physically represents a point-to-point transmission design alternative. The creation of design alternatives is thus accomplished through the instantiation of basic electrical apparatus classes. The task of class methods is to search the equipment database for the electrical apparatus which meet all requirements imposed by top-level knowledge and simulations. For example, the equipment belonging to the class "transmission" (shunt capacitors, SVC, series capacitors, shunt reactors, substations) can be instantiated, thus leading to the full design alternative. The process of "transmission" class instantiation has to be carried out for all possible alternatives found at the previous steps (top-level knowledge processing).

2.3.2.1.2 Simulation Procedures and Supporting Expert Systems

Simulations are run in order to adjust the heuristically-estimated values of series and shunt compensation so as to meet design specifications under steady-state and transient conditions. For example, load flow simulations are carried out, among other reasons, to find the amount of SVC under full load and light load conditions which will maintain a relatively flat voltage profile.

Insulation coordination [Gal90] is another special kind of simulation mostly based on heuristic expertise. Therefore, this simulation tool cannot be classified as a numerical procedure but rather within the group of supporting expert systems [Ata95-2]. Its purpose is to determine the insulating characteristics of insulator strings. More details related to the insulation coordination process are provided in Section 2.3.4.

Another supporting expert system which is implemented within TIDE is the "Line_design". The role of this module is to recommend the conductor size and the number of conductors per phase [Epri82] based on corona effects and the cost of losses.

The results obtained from all these simulations lead to the final selection of the pertinent electrical equipment. In addition, simulation procedures such as reliability, cost evaluation and multi-criteria analysis of all design alternatives are carried out at the last design step to rank designs according to the specified measures of performance [Lou96].

2.3.3 Protection System Design

The main role of protective relaying [Rus78,Bla87,Hor80,Mas56] in electric power system design and operation is two-fold: (i) The primary function is to accomplish the prompt removal from service of any component of the power system which is affected by a fault (short-circuit) or when it operates in an abnormal manner representing a potential danger to the rest of the system. The relaying equipment is accompanied in this task by circuit-breakers which perform disconnection of the faulty elements upon request by the relevant protective relays. (ii) The secondary function of protective relaying is to provide an indication of types and locations of failures or incipient failures.

The main objective of the protection design is therefore to select the proper relaying equipment and to specify their method of connection to enable the above-mentioned main protection functions to satisfy the input specifications. This is generally a complicated state-of-the art task based mostly on extensive engineering experience involving the following activities:

- Analysis of the system operational requirements and criteria.
- Study of the system configuration (single-line diagrams).
- Analysis and selection of feasible protection schemes which satisfy the specified system operation criteria.
- Selection of protection equipment (relays, instrument transformers and other auxiliary equipment).
- Evaluation of system performance and cost analysis.

A description of a proposed object-oriented knowledge-based model for protection system design is provided in the following sub-sections.

Considerable effort has been made to consolidate protection design knowledge and then to develop a knowledge-based tool which will assist protection engineers in carrying out a design task [Mas56]. Most of these tools have been developed using forward or backward chaining reasoning, using an inference engine to govern the execution of the rules. However, the inherent structure of protection design systems and the nature of the design knowledge favour an object-oriented approach to knowledge modelling. This section, therefore outlines the basic features of the proposed object-oriented model following the general concepts presented in the introduction (Section 1.3.2).

2.3.3.1 An Object-oriented Knowledge Model for the Design of Protection Systems

Two principal class structures are conceived: the "Design-Shell" class (Figure 2.5), which contains all information related to a particular design session and the "Protection_systems" class (Figure 2.6) encompassing configurations of numerous protection systems of different power system components. Apart from these classes, which constitute the design model, it is important to mention the relevant equipment database part presented in Figure 2.7 which depicts the class hierarchy organization of protective relays and is a member of the global equipment database (Figure 2.2).

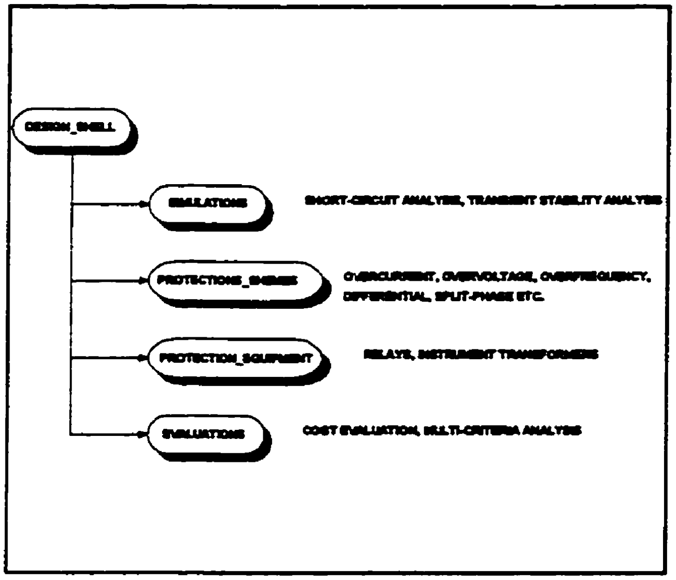

Figure 2.5: Design-session class for protection design.

As shown in figure 2.5, the "Design-Shell" class consists of four main class members namely "Simulations", "Protection_schemes", "Protection_equipment" and "Evaluations". The class "Protection_schemes" contains selected feasible protection systems which meet the specified design criteria (reliability) while the class "Protection_equipment" models protective equipment such as protective relays, instrument transformers and other auxiliary equipment. The class "Evaluations" contains results of cost and multi-criteria evaluation of design alternatives while the class "Simulations" preserves results of fundamental simulations such as insulation coordination and short-circuit analysis.

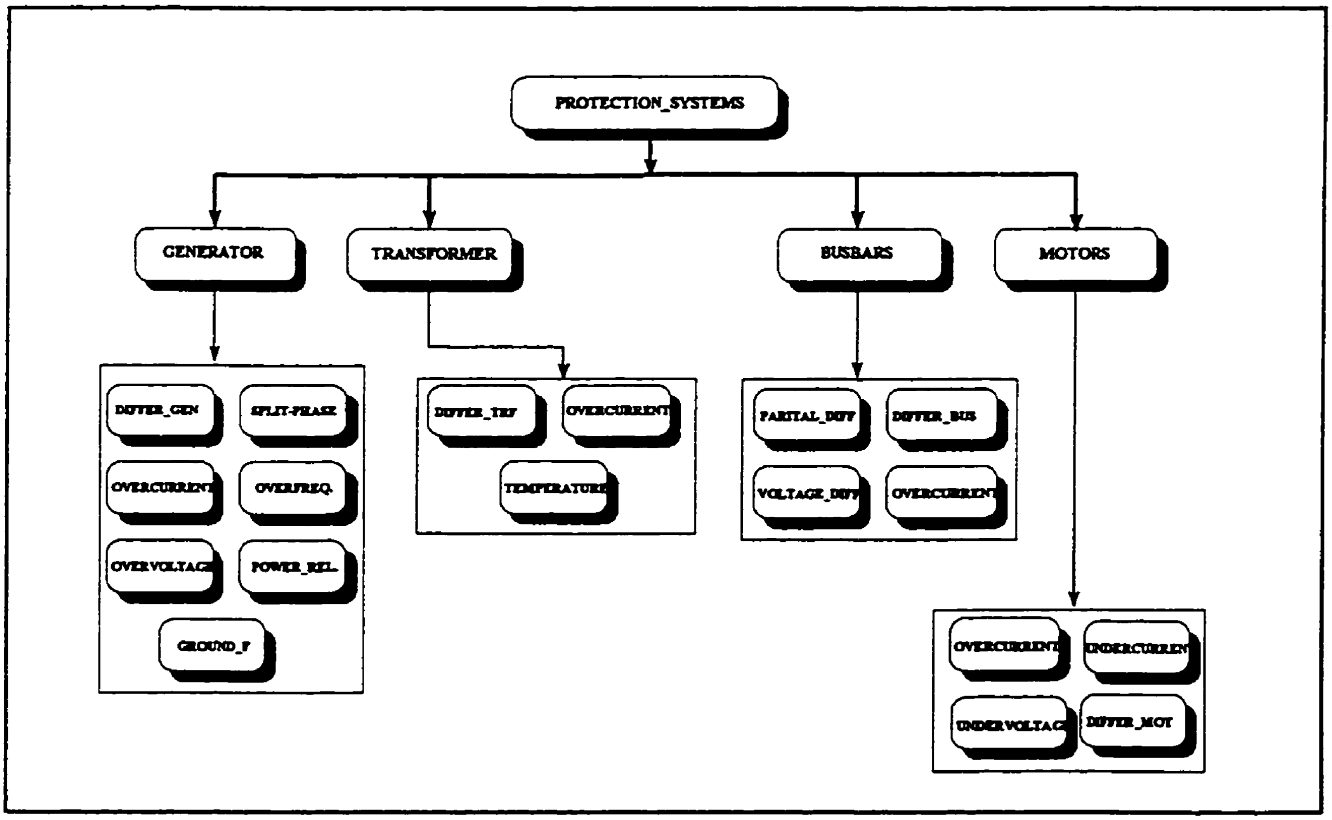

Figure 2.6: Protection systems.

Figure 2.6 presents a structure of the "Protection_systems" class whose sub-classes correspond to basic elements of any power system, namely, generators, motors, transformers, power lines and busbars. Since there exist various ways of protecting these elements, each of the above-mentioned sub-classes is further expanded to contain several possible protection systems gleaned from experience. Thus, a generator may have differential, split-phase, ground fault, power relaying, over-current, over-voltage and over-frequency protection systems each of which is modelled by a corresponding class member of the class "Generator_prot". The system which will be selected and attached to the class "Protection_schemes" (Figure 2.5) is determined through processing of the domain knowledge described in the following paragraphs.

2.3.3.2 Knowledge Processing in Protection Systems

The knowledge which is processed to select feasible design schemes, thus creating instances of the class "Protection_schemes" is classified as a *top-level* knowledge in the protection system design model. The main design activities involve *top-level* knowledge processing as summarized below:

• Identification of a given system for which a protection is to be designed (larger power network, smaller distribution network, substation, transmission line etc.).

• Identification of the basic system sub-components which require protection (generators, transformers, bus sections, power lines, feeders etc.).

• Selection of required protection systems (differential, over-current, under-voltage etc.) for each sub-component found in the previous step. The configuration of each protection system is specified here (e.g. differential protection requires at least two current transformers and differential relay) but not the pertinent equipment characteristics.

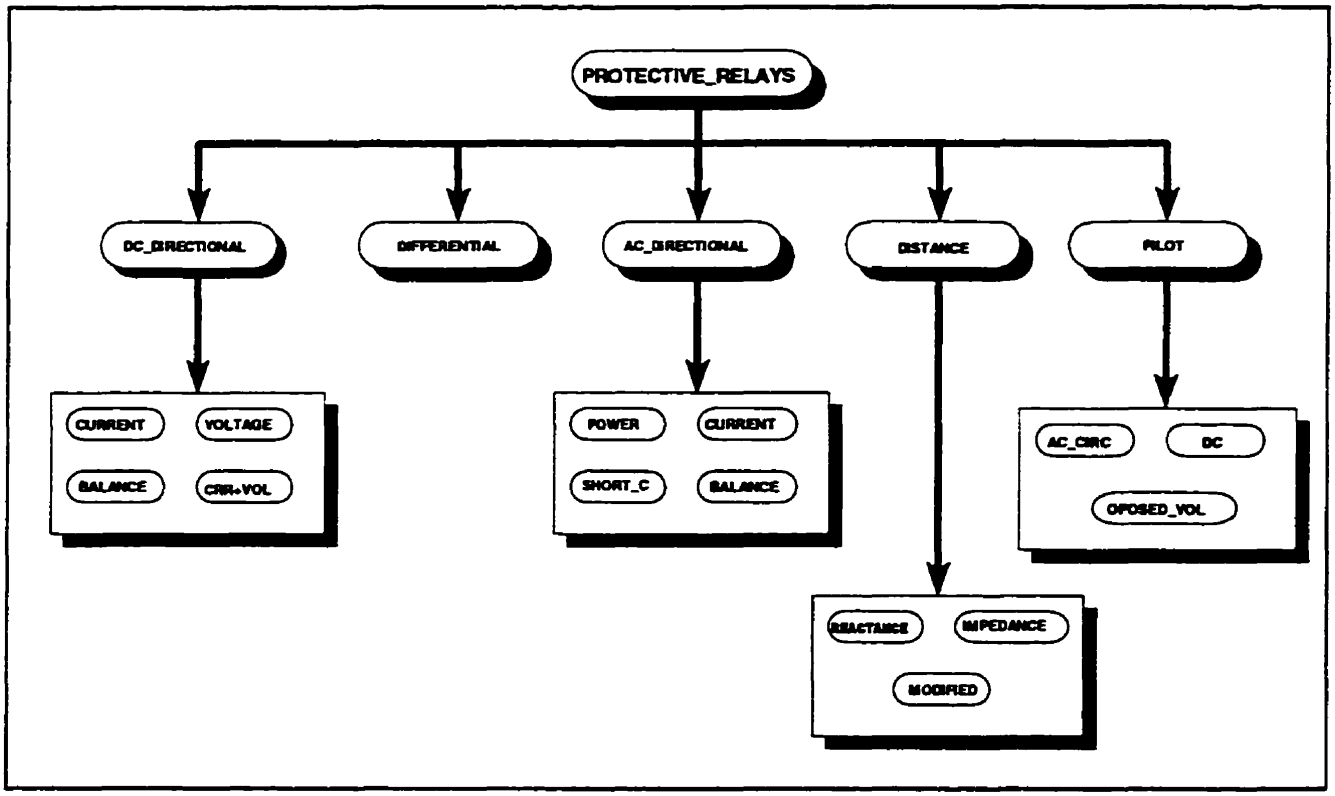

Figure 2.7: Protective relays database class hierarchy.

• Different options regarding the arrangement and the coordination of protection systems are considered here. There may be several ways to define protective zones for each element in a given system. The role of top-level rules is to establish feasible primary and back-up protection zone arrangements for each protected element [Mas56] preserving selectivity as an important characteristic of protection systems (the ability of a system to recognize and disconnect only the targeted element). In addition, top-level knowledge is processed in order to determine the necessary adjustments and characteristics of protective relays and instrument transformers (burden, class, number of cores). The top-level knowledge rules are distributed over the methods of the class "Protection_schemes" (Figure 2.5) as well as over the methods belonging to the classes in the "Protection_systems" class hierarchy (Figure 2.6). Thus, rules which perform the global coordination of protection zones are contained in the class "Protection_schemes", while rules which define relay parameters and instrument transformer characteristics are contained in the methods of the "Protection_systems" classes. For example, having identified protection systems in a given substation, one may wonder whether substation busbars and power transformers should be protected separately or whether, rather, a common differential protection scheme should be developed for both. This kind of problem is usually resolved by "Protection_scheme" class methods. In addition, one may need to specify the number of cores, the accuracy class and the burden of current transformers implemented in the differential protection. This activity is carried out by the methods of the classes "Differ_trf" and "Differ_bus" which are shown in Figure 2.6.

The low-level knowledge employed here is processed to search the equipment database and select the electrical equipment which will satisfy the given design criteria. Similarly to the point-to-point transmission design, low-level knowledge rules check whether short-circuit and insulation capabilities of the equipment are sufficient for operation under normal and faulty conditions.

2.3.3.3 Simulations in Protection System Design

Two type of simulations are performed here: simulations yielding system parameters used to select electrical equipment, namely, short-circuit analysis and insulation coordination, and the evaluation of design alternatives with respect to the cost and specified criteria preferences. The former are contained in the class "Simulations" while the latter constitute the class "Evaluations".

2.3.4 Insulation Coordination Expert System (ICES)

The insulation coordination process consists of the selection of the electric strength of equipment in relation to the voltages which can appear in the system for which the equipment is intended. It takes into account the service environment as well as the characteristics of available protective devices [IEC71].

Insulation coordination is a frequently performed activity in power system design when substation or transmission designs are concerned. Insulation coordination is carried out to provide standard withstand voltage levels for electrical equipment as well as phase-to-ground, phase-to-phase and longitudinal air clearances and characteristics of insulator assemblies.

According to the classification provided in Figure 2.1, the insulation coordination module belongs to the group of supporting expert systems. One version of an insulation coordination expert system has been already developed at McGill University [Gal90] based on a forward-chaining classical rule-based approach. However, in keeping with the object-oriented philosophy of PSIDE, a new version of the insulation coordination model has been developed. The objective of this section therefore is to present an object-oriented knowledge-based system for insulation coordination which could be implemented in the proposed global model for power system planning and design (Figure 2.1). In addition to the knowledge associated with insulation coordination in transmission system design, the proposed model will also incorporate insulation coordination in substations. The basic features of this module are discussed in the following sub-sections [Bel96-1,Bel96-2].

2.3.4.1 An Object-oriented Knowledge Model for Insulation Coordination

Two main complex classes and one class hierarchy constitute the object-oriented knowledge model of the insulation coordination process. These are the "Design-Shell" class, the "Insulation_process" class and the class hierarchy "Insulation" which are discussed in the following sub-sections.

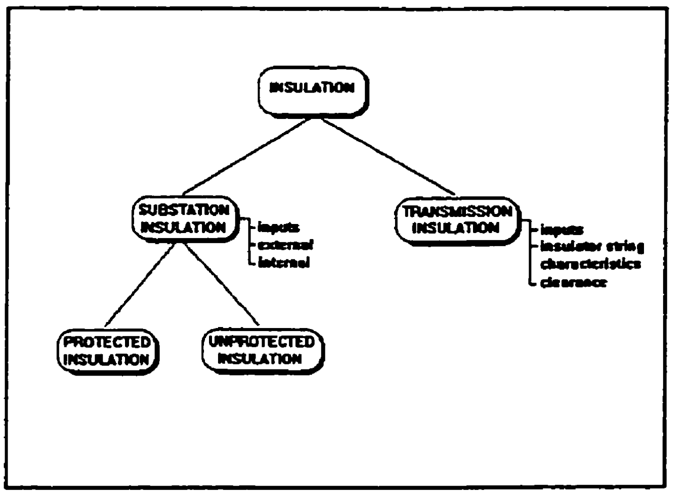

Figure 2.8: Insulation class hierarchy.

Insulation class hierarchy. From the insulation coordination point of view, the concept of insulation can be considered as an independent entity. Thus, a class named "Insulation" is defined to represent any equipment in a power system and as such is designated to be a top class in the class hierarchy model of the insulation coordination process as shown in Figure 2.8. As mentioned above, there exist two main insulation coordination activities in the power system design area, namely, insulation coordination in substations and insulation coordination in transmission design. The main sub-classes "Substation_Insulation" and "Transmission_Insulation" are derived from the top class "Insulation" preserving the knowledge related to the above-mentioned activities. Furthermore, the electrical equipment installed in substations can be either protected (by surge-arresters) or unprotected. This involves the creation of two additional sub-classes "Protected_Insulation" and "Unprotected_Insulation" derived from the class "Substation_Insulation" containing specific knowledge related to the insulation coordination process when either protected or unprotected equipment is involved.

The "Insulation" class contains common attributes related to general insulation data such as standard withstand voltage values, protective levels of surge arresters, risk-of-failure curves, etc. As for the "Substation_Insulation" class, its attributes are inputs (overvoltages and environmental conditions) and two instances of the "Insulation_Process" class named "external" and "internal". These represent respectively the external and internal insulation characteristics of equipment. The attributes of the "Transmission_insulation" class are inputs (overvoltages and environment) and the characteristics of insulator strings and air gaps.

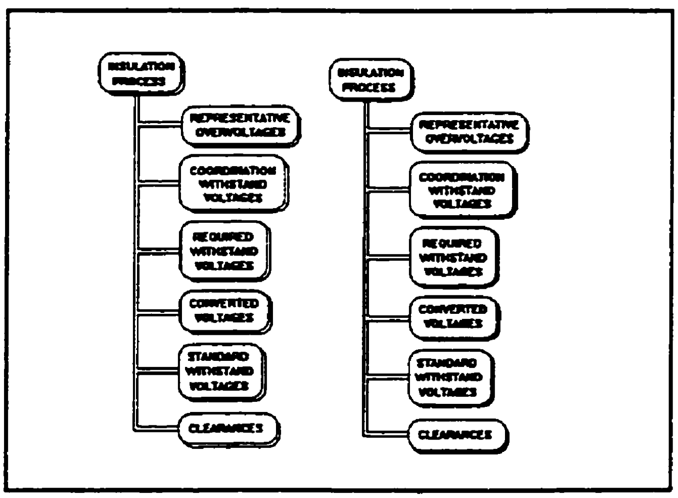

Figure 2.9: Insulation_process class.

The Insulation_Process class. The "Insulation_Process" class (Figure 2.9) is defined in order to model the insulation coordination procedure which consists of the following steps: determination of representative, coordination withstand, required and standard withstand overvoltages as well as air clearances. Consequently, the classes: "Representative_Overvoltages", "Coordination_Withstand_Voltages", "Required_Withstand_Voltages", and "Standard_Withstand_Voltages" are members of the

"Insulation_Process" class. Accordingly, attributes of each of these classes are values of the voltages at each step. In addition, the class "Clearances" contains values of air clearances phase-to-ground, phase-to-phase and longitudinal.

The Design-Shell class. This class contains the complete information related to the particular design session. Thus, if both substation and transmission design are considered, both members "Design_Substation" and "Design_Transmission" are instantiated. The class "Design_Transmission" is defined as a part of the Insulation class hierarchy and corresponds to the class "Transmission_Insulation". The class "Design_Substation" also contains an aggregate class member "Voltage_Levels". The term aggregate means that there may be several instances of that class depending of the number of voltage levels in the substation. As shown in Figure 2.10, the members of the class "Voltage_Levels" belong to the classes "Protected_Insulation" and "Unprotected_Insulation" which are also defined in the "Insulation" class hierarchy.

2.3.4.2 Knowledge Processing in Insulation Coordination

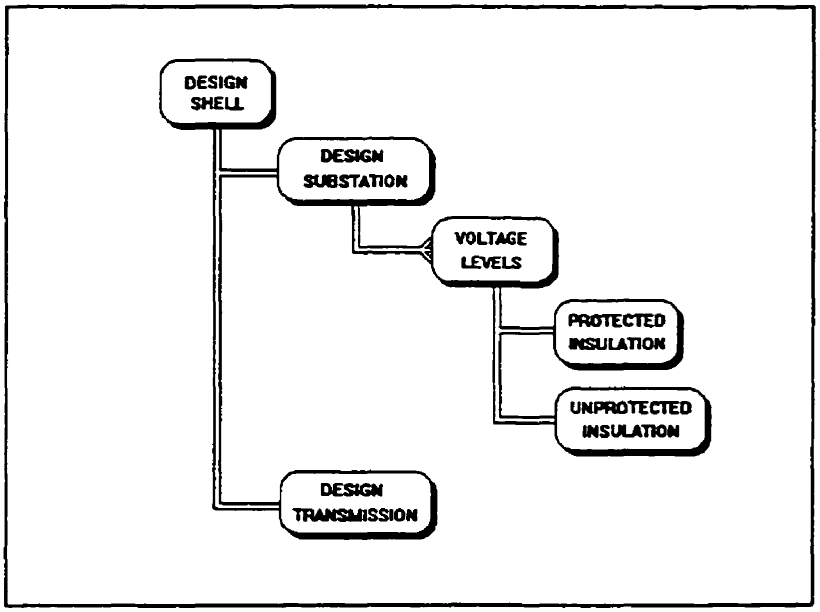

Figure 2.10: Design-session class for insulation coordination.

According to the IEC Application guide [IEC71], the insulation coordination process consists of four basic steps: determination of representative overvoltages, coordination withstand voltages, required withstand voltages and standard withstand voltage levels. The knowledge which is processed at these steps depends on the type of insulation (external, internal) and on the existence of protective devices. Thus, where protected equipment is concerned, the above steps are accomplished by using methods of the class Protected_Insulation. On the other hand, when dealing with unprotected equipment, methods from the Unprotected_Insulation class are invoked. The use of polymorphism is particularly advantageous here since there exist several methods which perform the same kind of task involving different knowledge rules. For example, the determination of coordination withstand voltages for slow-front overvoltages is accomplished by using the class method from the "Protected_Insulation" class based on a deterministic approach for protected equipment. Where unprotected equipment is concerned, the same method from the class Unprotected_Insulation is employed relying in this case on the statistical approach. The statistical approach can also be applied to protected equipment merely by assuming that the insulation is unprotected.

Apart from processing the domain knowledge, each method generates explanations about the design activity.

2.3.5 Substation Design

The design of electrical substation represents a very complex knowledge-intensive problem involving several large areas of expertise such as single-line diagram selection, insulation coordination, short-circuit and load flow studies, equipment selection, protection, reactive power management, reliability analysis and cost evaluation. The design of substations is a frequently required task in any power electrical system as a result of load growth, generation expansion and voltage control needs. As such, the substation design problem occupies an important place in the proposed integrated knowledge-based model for electric power system planning. One of the objectives of this research is therefore to develop one complete knowledge-based system which integrates, preserves and supports substation design tasks. This example demonstrates all the powerful features and advantages of the object-oriented approach to solve complex power system design problems. The following chapter provides detailed description of the developed prototype for the preliminary design of electrical substations [Ata94,Ata95-2].

3. AN INTELLIGENT SUBSTATION DESIGN ENVIRONMENT

3.1 Summary

This chapter presents in detail an intelligent computer environment for the design of substations (SIDE, Substation Intelligent Design Environment) based on the object-oriented paradigm described in Chapter 1 [Ata94]. This tool integrates a diverse set of substation design and simulation activities into a powerful and friendly software package.

The term *intelligent* as used in this thesis should be interpreted as the capability to process a broad knowledge base and to produce a set of complex design alternatives (in this case substations) which meet a given set of basic specifications. The "intelligence" in SIDE is present in two forms: Knowledge within rules and procedures and the distribution of this knowledge over well-structured classes of objects.

The development of SIDE is motivated by the following facts:

• The design of substations is a frequently required task in any power system as a result of load growth, generation expansion and voltage control needs. As one example, in the Montreal area with a load of approximately 15,000 MW, about 200 different substation design projects are carried out annually ranging from 25 kV to 735 kV at a cost of several hundred million dollars.

• Many aspects of substation planning, design, operation and maintenance are highly knowledge-intensive, that is, their execution depends strongly on human expertise acquired through years of experience rather than on specific numerical procedures.

• Expertise in substation design and operation is becoming less available due to the retirement of experienced personnel. Furthermore, substation design expertise is generally not centralized but, rather, spread throughout numerous departments, companies, data bases, manuals and people. An integrated knowledge-based substation design tool would go a long way therefore to preserve and make use of this expertise.

The general objective in this part of the research was to develop a knowledge-based tool to integrate, preserve and support those tasks inherent to substation design. This tool fulfills this objective by bringing together the principal activities and data related to the electrical engineering design of a substation. It produces a number of potential designs which satisfy the given design criteria such as short-circuit levels, insulation withstand voltages and reliability. The designs generated by SIDE include: the definition of the main substation equipment, their general electric specifications, the single-line diagram of a substation, as well as a detailed report describing the design performance including reliability and cost.

The main knowledge-based system architecture outlining all the basic system subcomponents and modules of SIDE is introduced in Section 3.2. The detailed description of the object-oriented knowledge models including the description of the domain knowledge, knowledge representation and knowledge processing is provided in Section 3.3 to 3.8. Finally, the basic characteristics of the tool's graphical user interface are presented in section 3.9.

3.2 System Architecture

As shown in Figure 3.1, the system architecture of SIDE is conceived to function on the client-server principle. The server is the brain which contains the object-oriented design knowledge models. It manages the system databases and performs knowledge processing to generate a set of feasible design alternatives. The client is the graphical user interface which enables users to access different design facilities, input design specification data and examine output design alternatives and databases. Several users can access the design tool simultaneously. The server is developed under the C++ programming language [Pra91] for its object-oriented capabilities and portability while the clients are based on Tcl/Tk [Ous93], a powerful environment for graphical user interface development.

The following is a summary of the four basic components of the server seen in Figure 3.1 as part of the overall system architecture of SIDE.

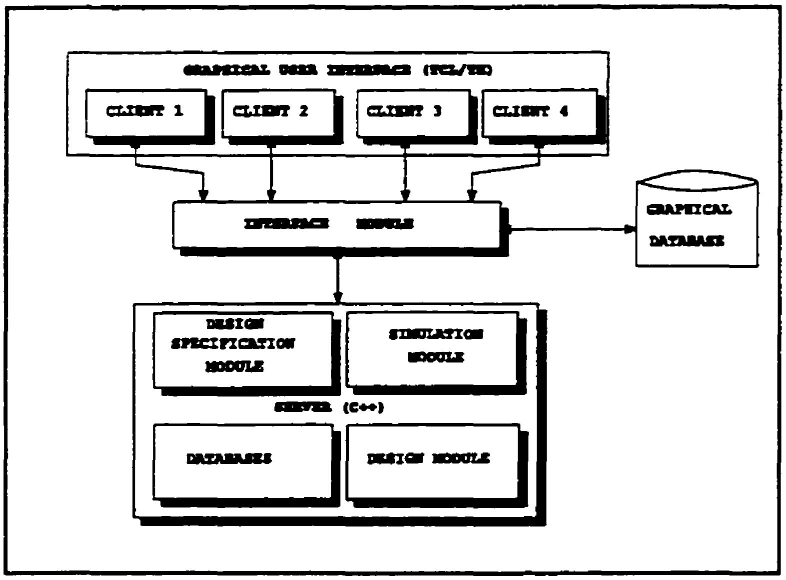

Figure 3.1: The knowledge-based system architecture.

The Design Specifications Module is described by an object-oriented class structure whose main purpose is to maintain a database of input design specifications.

The Simulation Module contains diverse simulation procedures which are used in the design process (load flow, short-circuit, insulation coordination, reliability, cost analysis etc.).

The System Databases contain data on all substation electrical apparatus, system design constants used in some simulation procedures and existing input specifications and output designs. The graphical database (developed in Tcl/Tk) is not a part of the server but it communicates with the server through the interface module and holds a graphical representation of all substation equipment and single-line diagram components including complete single-line diagrams.

The Design Module coordinates the design knowledge processing and generates and evaluates output design alternatives.

The client subcomponents are menus, windows, buttons and dialogue boxes providing the user with friendly access to all system facilities. To enable a connection between server and clients (C++ and

Tcl/Tk), an interface module has been developed which contains various interface C functions.

3.3 Object-oriented Model of SIDE

The domain knowledge in substation design can be subdivided into the following five categories:

- Structural Composition of a Substation (Section 3.4)
- Design Specifications of SIDE (Section 3.5)
- Simulation Procedures (Section 3.6)
- Substation Design Methodology (Section 3.7)
- Electrical Equipment (Section 3.8)

These sections outline at some length the steps whereby the object-oriented model for substation design is constructed beginning with the description of a substation and ending up with its principal equipment components. To lighten the burden on the reader, these sections can be considered as entities in themselves: they are more or less self sufficient: Nevertheless, their contents are related so that taken together they form the story of SIDE. The chapter concludes with a discussion of the Graphical User Interface.

3.4 Structural Composition of a Substation

An electric substation is an assembly of power equipment whose function is to transform electric energy or to facilitate the switching of lines or cables so as to control the power flow and voltage levels in a power system. A typical transformer substation consists of the following five main composite groups of electrical equipment:

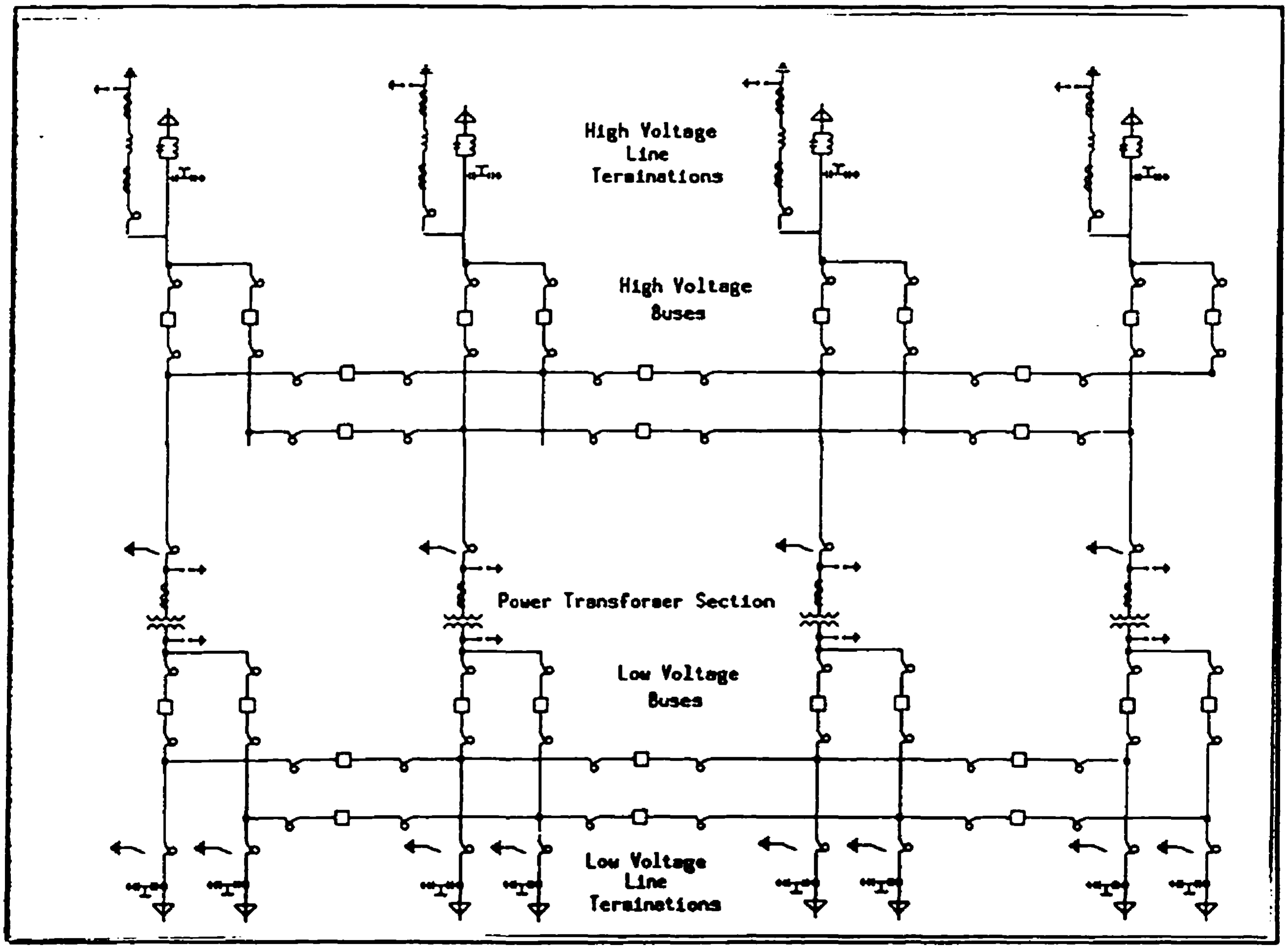

Figure 3.2: Typical substation single-line diagram.

(1) High-voltage line terminations.

(2) High-voltage busbars.

(3) Power transformers and associated equipment.

(4) Low-voltage busbars.

(5) Low-voltage line terminations.

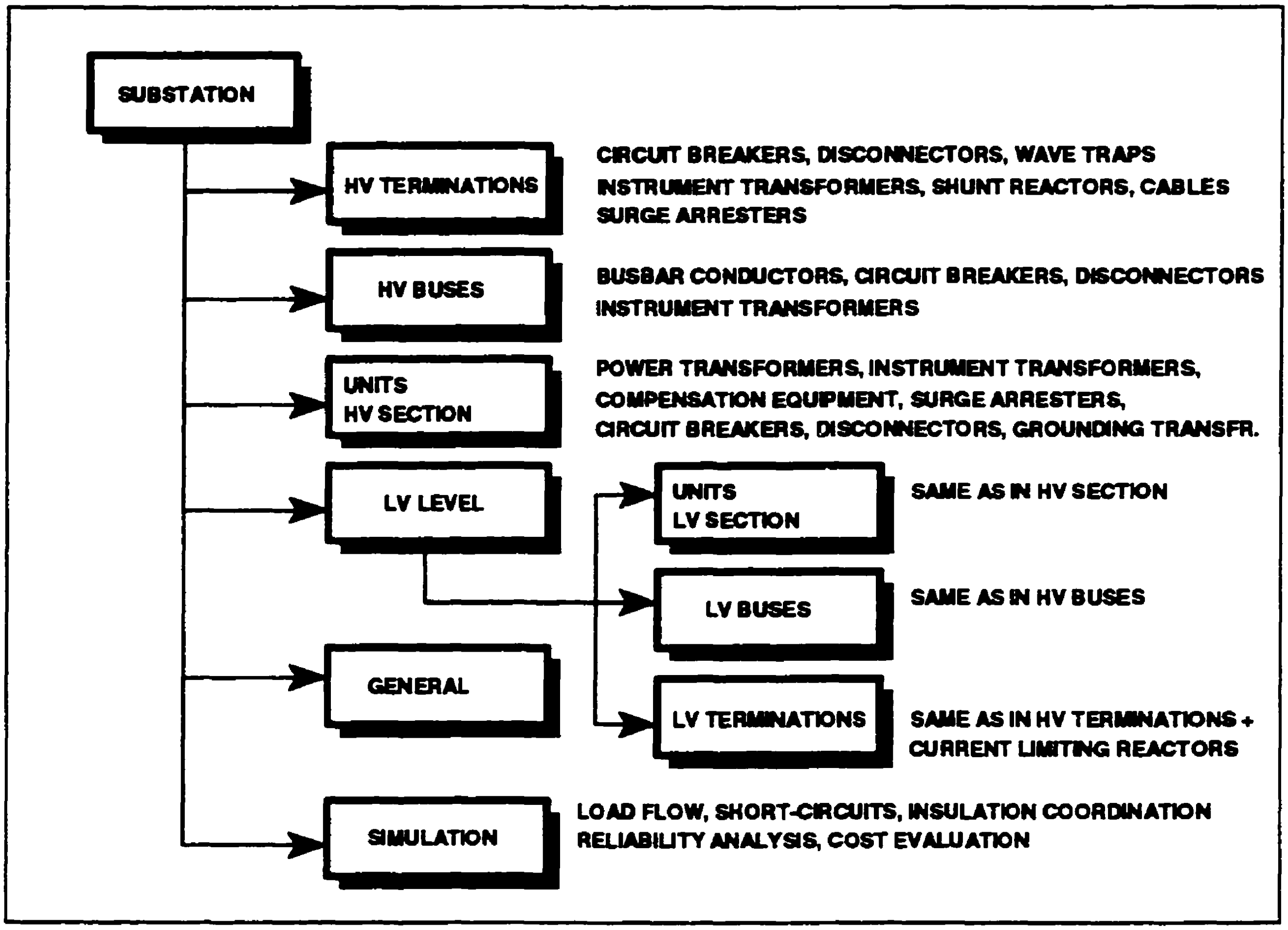

Figure 3.3: Substation class structure.

Figure 3.2 shows a single-line diagram of a typical 735/315 kV substation where its five main *composite groups* are identified. The knowledge-based system discussed here, SIDE, takes advantage of this natural composition of a substation in order to systematically structure the knowledge associated with its design. Thus, the whole substation can be considered as being a class containing several main class members corresponding more or less to the substation basic composite groups.

Figure 3.3 displays the substation main class structure, i.e. the class "Substation". The classes "HV_Terminations", and "HV_Buses" model the composite groups that belong to the high-voltage part of the substation. The class "LV_Level" was conceived to model the substation low-voltage part whose main components are the classes representing the substation composite groups located in the low-voltage part ("LV_Buses", LV_Terminations") including the transformer and compensation groups (the class "Units" models both low-voltage and high-voltage sections). Apart from the classes modelling the five constituent groups, the class "Substation" contains the classes "Simulation" and "General". The former encapsulates the knowledge related to the simulations which are usually carried out in substation design, i.e., it comprises methods which perform insulation coordination, short-circuit studies, reliability analysis, etc.. In addition, the same class preserves the results of all these simulations later used in the design process. The class "General" consists of general design information such as design title, number of voltage levels and number of incoming/outgoing lines.

The following subsections discuss in detail the domain knowledge and the corresponding object-oriented knowledge models associated with the substation composite groups.

3.4.1 High and Low Voltage Line Terminations of a Substation

High-voltage line terminations represent connection points for high-voltage incoming/outgoing lines. The typical subcomponents of the high-voltage line terminations are the following electrical apparatus: lines/cables, circuit breakers, shunt reactors, disconnectors, grounding switches, surge arresters, instrument transformers and communication facilities (wave traps). There exist several possible arrangements for HV terminations depending on the electrical apparatus to be installed. Twelve of the most common termination configurations are presented in Figure 3.4 and discussed as follows:

The HV line terminations *HV_Term1, HV_Term2* as well as *HV_Term11 and HV_Term12* are mostly implemented at extra-high voltage levels of 500 kV and above. Their common characteristic is that they possess a shunt reactor accompanied by switching and protective equipment such as a surge arrester, circuit breaker and current transformers. The shunt reactor is required to limit possible overvoltages which can occur in extra-high voltage transmission systems. These line terminations also include a potential transformer to enable voltage measurements, a main disconnector which executes the disconnection of the line from the busbars, and a line conductor which interconnects all these components. These components (potential transformer, disconnector and conductor) are common

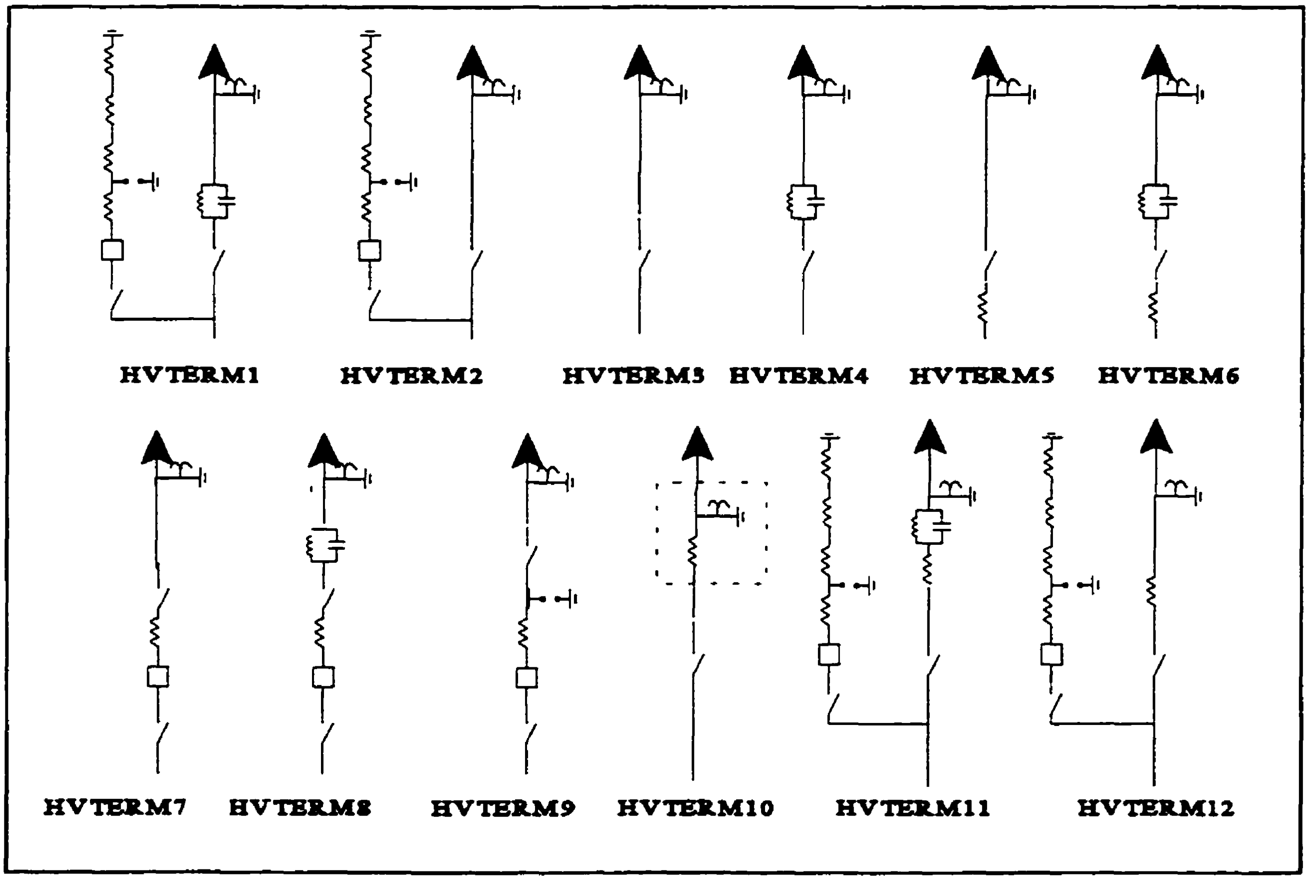

Figure 3.4: Substation line terminations.

not only to these four but to other configuration types. In addition to these common properties, the line termination configurations have their own particular characteristics. Thus, the configurations *HV_Term1* and *HV_Term11* possess wave traps to enable communication and signal transmission

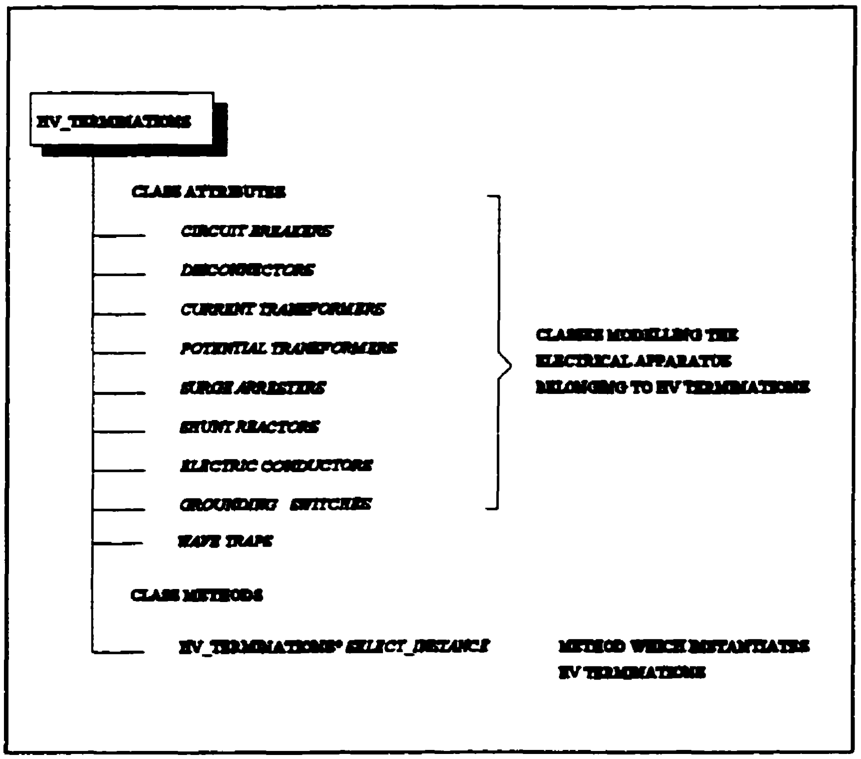

Figure 3.5: High voltage terminations class model.

while *HV_Term12* has an additional current transformer to enable required measurements of electric power.

The line terminations *HV_Term3*, *HV_Term4*, *HV_Term5* and *HV_Term6* are standard configurations implemented at all voltage levels. Apart from the common elements (potential transformer, disconnector and conductor), *HV_Term4* and *HV_Term6* have a communication facility (wave trap). Furthermore, the configurations *HV_Term5* and *HV_Term6* have an additional current transformer enabling electric power measurements.

The configurations *HV_Term7* and *HV_Term8* possess a circuit-breaker to accomplish the disconnection of the line if the presence of a fault has been detected. These line terminations are implemented when the corresponding HV busbars do not possess enough circuit-breaker facilities to disconnect the lines.

HV_Term9 is the only configuration having a cable conductor. Since a cable contains non-self-restoring insulation (insulation material that can be permanently damaged) the presence of a surge arrester is required.

HV_Term10 contains one compact measurement package (current transformer-potential transformer)

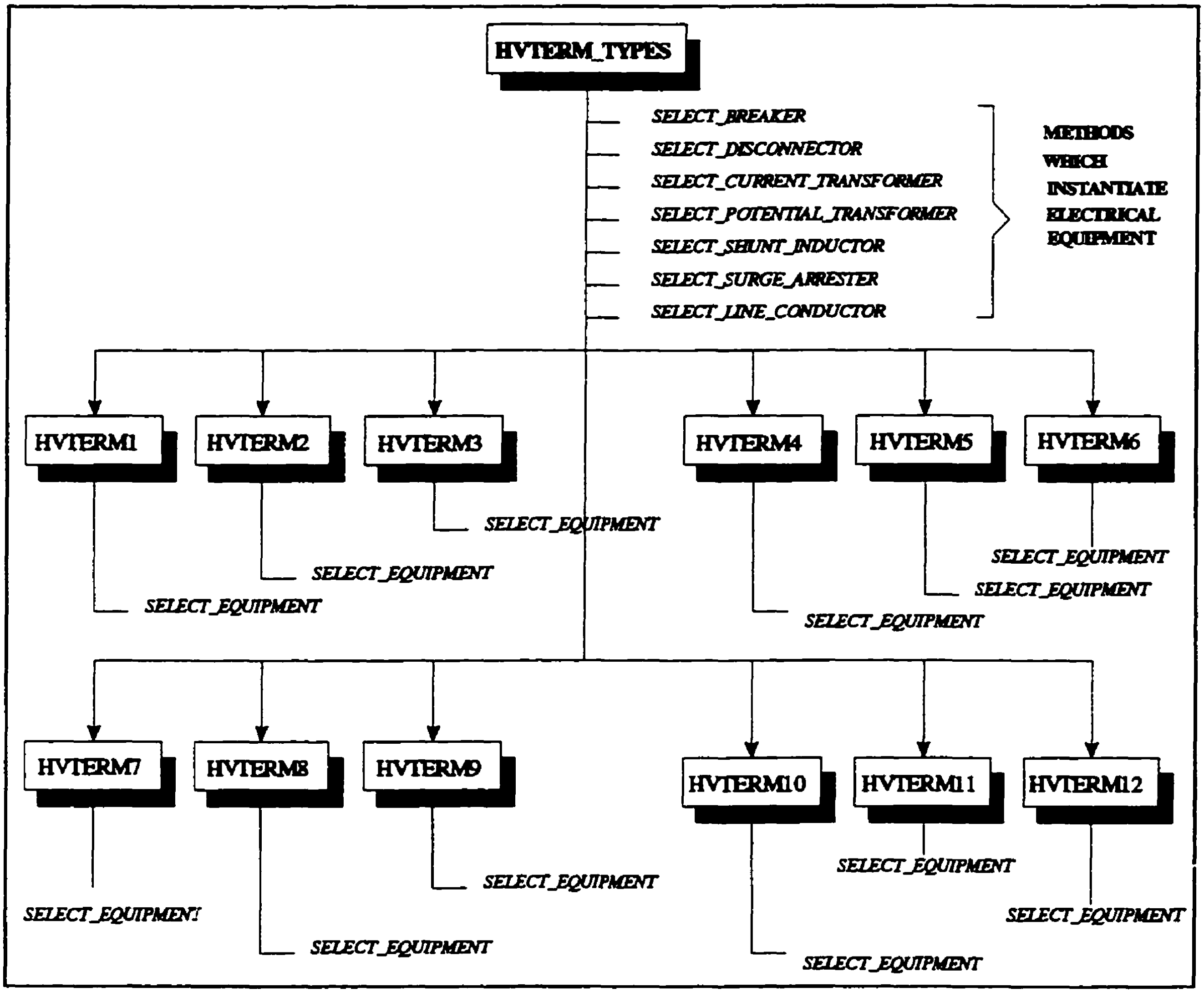

Figure 3.6: Class hierarchy modelling different types of line terminations.

to enable measurement of electric power.

Apart from the above-discussed configurations of line terminations, there are various other line termination arrangements which can be considered. Those depicted in Figure 3.4 are the typical ones included in the database of SIDE. One of the advantages of the object-oriented approach in knowledge modelling is the flexibility to easily upgrade, that is, the addition of a new configuration to the existing knowledge base is accomplished very efficiently. The object-oriented knowledge models of high-voltage line terminations are now described in more detail.

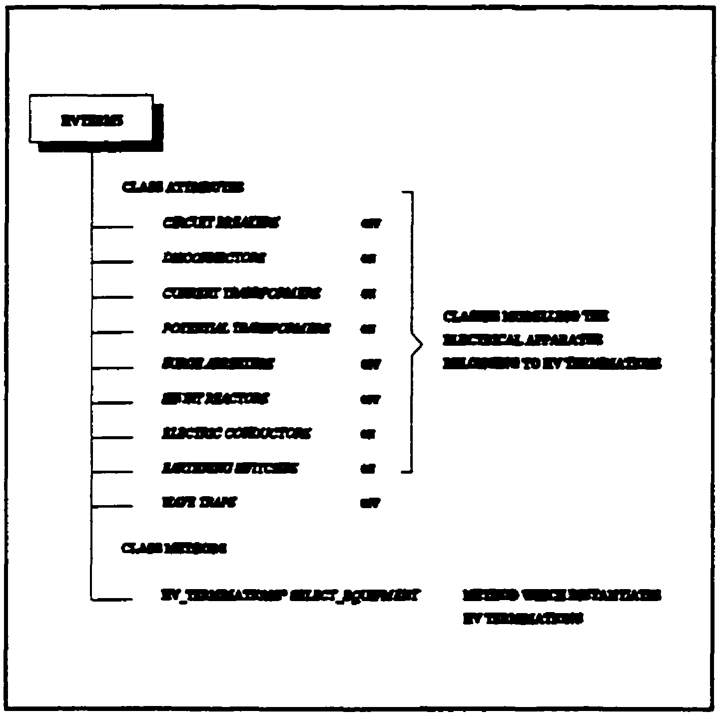

Figure 3.7: An example of a HV line termination class model (HV_Term5).

One class structure and one class hierarchy constitute the object-oriented model of HV line terminations. The class structure "HV_Terminations" shown in Figure 3.5 consists of class members representing all types of electrical equipment which may belong to the HV terminations composite group. In addition, this class contains a method named "SelectInstance" which governs the class instantiation and which will be addressed in more detail at the end of this section.

The class hierarchy presented in Figure 3.6 models the HV termination arrangements shown in Figure 3.4. Thus, a class named "HVTerm_Types" at the top of the class hierarchy contains methods which perform the *complete* selection of the HV termination's electrical apparatus. The attribute *complete* means that, not only are the electrical properties defined by invoking the appropriate electrical apparatus class constructor, but that the name, location and function of this apparatus within the substation are also specified. The subclasses of the "HVTerm_Types" class are models of the different HV termination arrangements shown in Figure 3.4.

Figure 3.7. presents a class model of one line termination (*HV_Term5*). Apart from inheriting methods from their parent class, each of these subclasses possesses the method named "SelectEquipment". This method entirely defines the equipment configuration of each HV termination arrangement by selectively instantiating only those electrical apparatus (marked “ON” in Figure 3.7)

which belong to this arrangement. As shown in Figure 3.7, the object created by this method is of type "HV_Terminations" which means that the execution of the method results in the construction of one instance of the class "HV_terminations". As could be concluded, different types of HV terminations are created by executing the method "SelectEquipment" from different subclasses. For example, if the method is invoked from the class "HVTerm5" the corresponding arrangement (*HV_term5* in Figure 3.6) will be created. This is a good example of polymorphism since each subclass contains a method with the same name (Select_Equipment) performing the same type of task (instantiation of the equipment pertinent to the particular HV termination) but with different a function (not the same equipment are instantiated for each arrangement). The instantiation of electrical equipment is accomplished using methods inherited from the top class "HVTerm_types" which are invoked in sequence within the method "Select_Equipment". The addition of a new HV termination arrangement can be easily accomplished by defining the appropriate "Select_Equipment" method of the additional subclass in the class hierarchy tree.

The instantiation process of "HV_termination" class is carried out in following steps:

•The method "SelectInstance" from the class "HV_Terminations" is invoked first. The parameters passed to this method are the system design specifications (an instance of the class "System_Input" from Section 3.5), the results of the simulation procedures (an instance of the class "Simulation" from Section 3.6), as well as the single-line diagram configuration of the substation (an instance of the class "SLDiagram" from Section 3.7). Depending on the type of HV termination arrangement which is provided as a part of the single-line diagram configuration, the method will select the corresponding subclass from the "HVTerm_types" class hierarchy (Figure 3.6) and pass the information regarding the system inputs, the proper names of the electrical apparatus and the location of this HV termination in the substation, to the method "Select_Equipment of the chosen subclass.

• The method "SelectEquipment" is then run in order to instantiate the electrical apparatus belonging to the chosen HV termination arrangements. For example, if the *HV_Term1* configuration is to be selected, the method "SelectEquipment" from the class "HVTerm1" (Figure 3.6) will instantiate the following equipment classes (Figure 2.2, Chapter 2): "Sh_Induct" (shunt reactor), "S_arrester" (surge arrester), "Sh_Ind_Cb" (circuit breaker), "Potential" (potential transformer), "Current" (current transformer), "Standard" (disconnector). Thus, the HV termination part of the substation which corresponds to the *HV_Term1* arrangement is instantiated as a result of processing the method "SelectEquipment" from the class "HVTerm1". Similarly, the other arrangements of HV terminations can be constructed by invoking the method "SelectEquipment" from the corresponding subclasses in the class hierarchy (Figure 3.6).

As far as low-voltage line terminations are concerned, the same considerations and object-oriented models apply.

3.4.2 Substation High-Voltage and Low-Voltage Buses

The high-voltage and the low-voltage busbar systems in the substation are considered the most important elements of the single-line diagram. They represent connection points for high-voltage and low-voltage line terminations as well as transformer/compensation groups. The electrical apparatus which constitute substation busbars are bus conductors, current and potential transformers and switching equipment (circuit breakers and disconnectors). Several possible connections (busbar arrangements) can be defined depending on the required level of reliability and operational flexibility. The most common busbar arrangements are: different versions of double busbars (with/without sectionalizers, one/two breakers, U connection), breaker-and-half arrangement, ring and single-bus arrangement. Less frequently, one can come across busbar configurations such as triple-busbars, single-plus-transfer buses or tapped arrangement. Following is a detailed description of each of the above-mentioned busbar arrangements. Some typical substation busbar configurations are depicted in Figure 3.8.

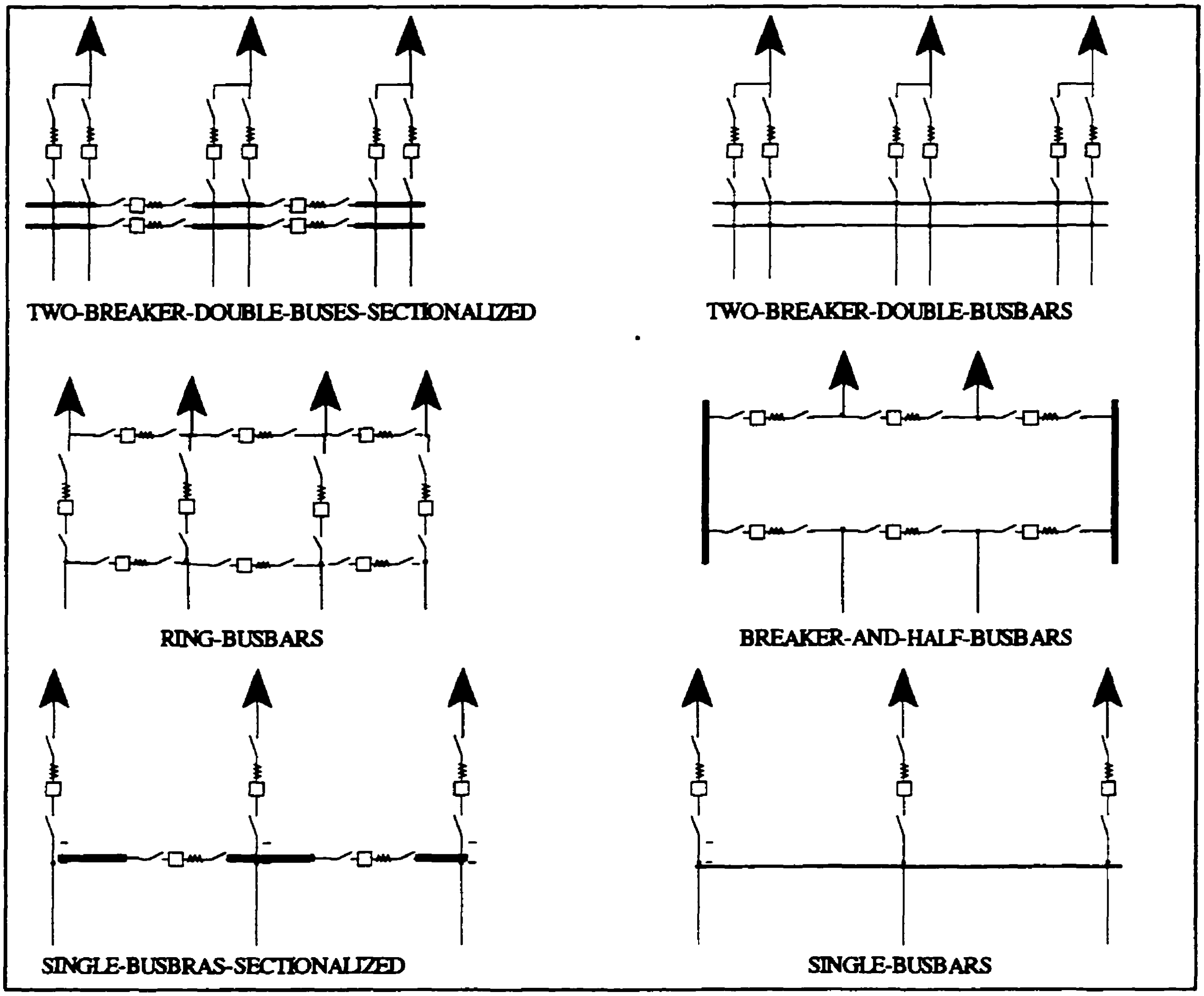

Figure 3.8: Some important substation busbar arrangements.

Double-busbar arrangements are preferred for larger installations (number of circuits greater than 2) usually at voltages above 120 kV. They are characterized by good operational flexibility (easier maintenance, possible separate operation from either bus) and a relatively high level of reliability. There are several forms of double busbars such as ***double-busbars-with-sectionalizers, double-busbars-without-sectionalizers, one-breaker-double-busbars, two-breaker-double-busbars*** or different combinations of these (e.g. two-breaker-double-buses with/without sectionalizers). The presence of sectionalizing breakers somewhat improves the reliability and the operational flexibility of the arrangement. Although more reliable and flexible, the arrangements with sectionalizing breakers are more costly. Other, less-frequently implemented double-busbar arrangements are the so-called *U-connection-double-busbar* arrangement and the *bypassed-double-busbars*. The former is used when low cost and space-saving (environment) are desirable while the latter is favored when better operational flexibility is required allowing each branch of the installation to be isolated for maintenance without supply interruption.

Similar to double-busbar arrangements, the *Breaker-and-a-half* arrangement is used mostly in large high-voltage (above 120 kV) installations. Fewer circuit breakers are needed here for almost the same operational flexibility as for *two-breaker-double-busbars* thereby decreasing the cost of equipment although installation costs could be greater. Uninterrupted supply is maintained even if one of the buses fails. Easy upgrade (possible extensions) is another advantage of this busbar configuration.

As far as *Ring-busbar* arrangement is concerned, each branch requires only one circuit breaker and, yet, it is possible to maintain each breaker without interrupting the load supply. This busbar configuration is frequently used in medium voltage substations. Sometimes, it is implemented as the first stage of a breaker-and-a-half arrangement having lower operational flexibility and reliability levels but also being less costly. It is often utilized in space-restricted substations for their relatively low space requirements when the number of incoming/outgoing circuits is relatively small.

Single-busbar arrangements can be realized in one of the following forms: *single-busbars, single-busbars-with-sectionalizers and bypassed-single-busbars*. The *single-busbars* arrangement is the least costly option suitable for smaller installations where the reliability and operational flexibility criteria are not the most critical ones. It is not usually implemented at voltages above 315 kV since a bus failure removes the whole substation from service. The operational flexibility is slightly increased by introducing the sectionalizing breaker (*single-busbars-with-sectionalizer*) which allows the substation to be split into two separate parts as well as the parts to be disconnected for maintenance purposes. Even better performance can be achieved by introducing a bypass busbar

Table 3.1: Busbar arrangement relative scores.

Arrangement / Criteria	Reliability	Operational Flexibility	Cost	Impact on the Environment
One-breaker-double-busbars	4	3	4	5
Two-breaker-double-busbars	8	5	3	4
One-breaker-double-busbars-sectionalized	7	6	1	3
Two-breaker-double-busbars-sectionalized	10	10	0	1
Bypassed-double-busbars	5	8	5	2
Breaker-and-half-busbars	9	9	2	6
Ring-busbars	6	7	6	9
Single-busbars	0	0	10	10
Single-busbars-sectionalized	1	1	8	8
Bypassed-single-busbars	2	2	9	7
Triple-busbars	3	4	7	0

thereby further increasing the maintenance capability.

The so-called *tapped-busbars* arrangement is used in the smallest substations having usually not more than two incoming circuits. Transformers are connected directly to the incoming lines such that the

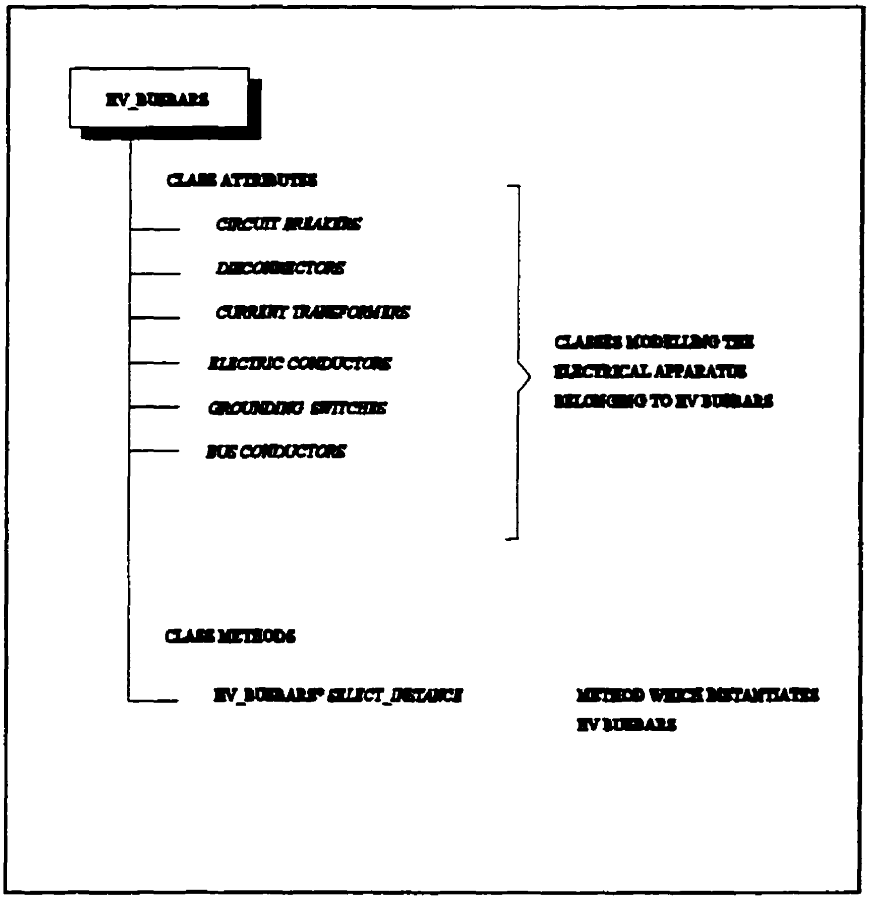

Figure 3.9: Substation HV busbars class model.

HV busbars in their real form do not exist. Very low reliability and operational flexibility counterbalancedc by low cost and spacing characterize this arrangement.

Table 3.1 summarizes the characteristics of each arrangement with respect to the four basic criteria (reliability, cost, operational flexibility and impact on the environment). Relative scores from 0 to 10 have been assigned to the various busbar arrangements based on experience.

The object-oriented knowledge modelling of substation busbars is accomplished in a manner similar to the case of substation line terminations. Thus, as outlined in Figures 3.9 and 3.10 the object-oriented class model of the above-described substation busbar configurations consists of two main classes, namely, the class "HVBus_Types" and the class "HVBusbars". The former constitutes a class hierarchy which models all the above-considered busbar arrangement where the class "HVBus_Types is on top of the hierarchy whereas busbar arrangements are modelled as its sub-classes inheriting common methods (methods which instantiate busbar equipment) as in the case of line terminations (previous section). The "HVBusbars" class represents a physical model of the substation busbars containing all its components (circuit breakers, disconnectors, bus conductors, instrument transformers) as class members.

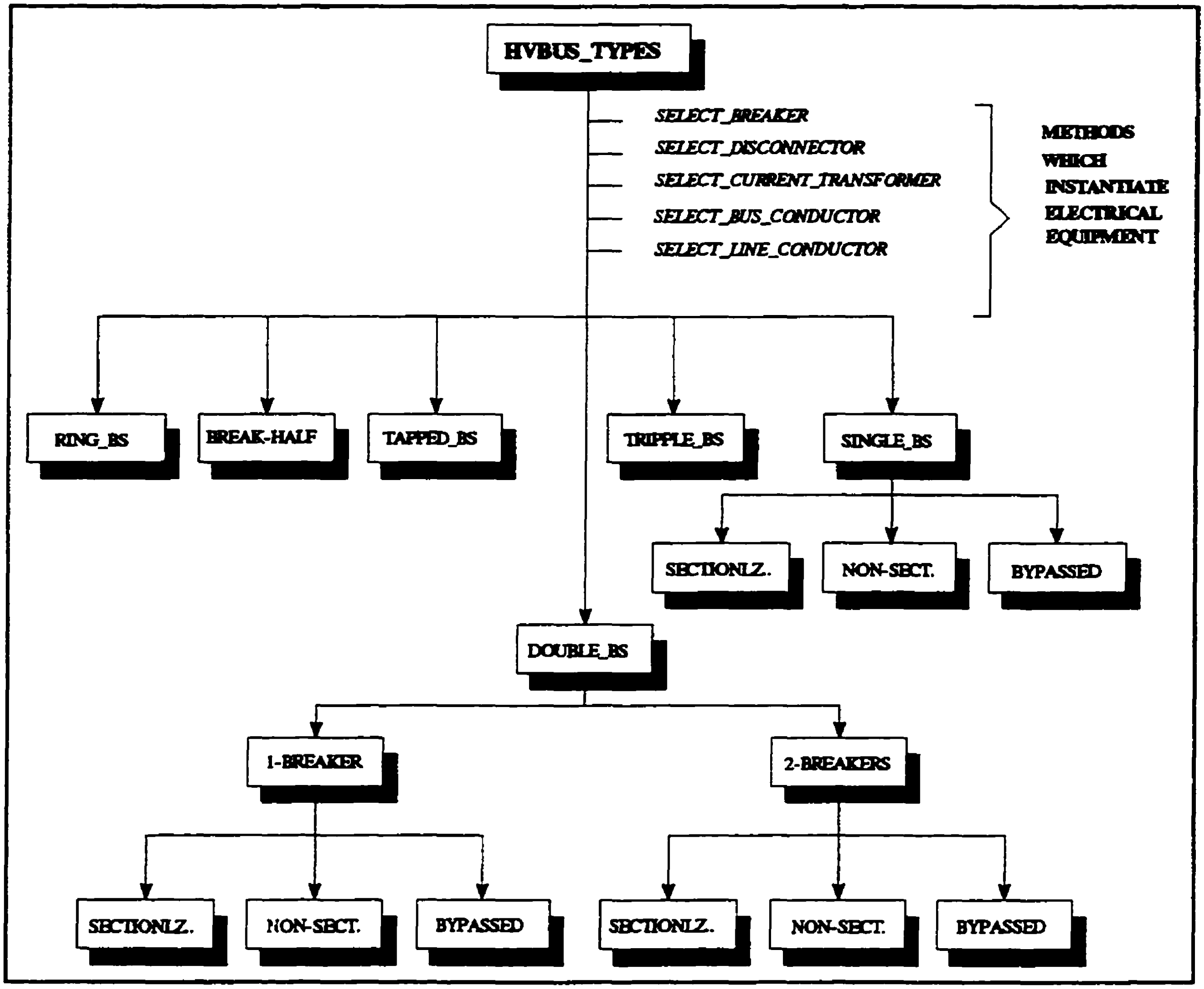

Figure 3.10: Substation busbars class hierarchy.

The instantiation process of substation busbars is completely analogous to that of substation line terminations. Thus, the method "SelectEquipment" is defined for each busbar arrangement encapsulating the knowledge related to the equipment configuration of that arrangement. The method "SelectInstance" is defined as a member of the class "HVBusbars" in order to govern the instantiation process of the overall busbar configuration (an instance of "HVBusbars"). The same instantiation procedure as described in detail in the previous section for substation line terminations is applied here for substation busbars.

Therefore, given the input arguments (single-line diagram, system input parameters and simulation results), the method "SelectInstance" is called upon first in order to pick up the appropriate subclass of "HVBus_types" hierarchy (the previously selected busbar arrangement). The method "SelectEquipment" from the selected subclass is then invoked to carry out the instantiation of electrical equipment belonging to the chosen busbar arrangement. The electrical equipment involved here is basically switching equipment, current transformers and bus conductors and since all of these apparatus are present in almost all busbar configurations, the method "SelectEquipment" is only slightly different for the various class models of busbar arrangements.

3.4.3 Substation Transformer and Compensation Groups

Transformer/compensation groups (TC groups) contain power transformers as their main component plus pertinent compensation, protective and switching apparatus such as surge arresters, current and potential transformers, disconnectors, circuit breakers and grounding transformers. The role of TC groups is to accomplish the connection between different voltage levels in a substation and to perform reactive power compensation by means of compensation equipment such as SVC (static var compensator) or capacitor banks are implemented. Unlike substation busbars or line terminations, where the number of considered arrangements was relatively small, numerous possible configurations for TC groups can be taken into account depending on the insulation coordination considerations, busbar arrangements, compensation and protection requirements. Figure 3.11 outlines the proposed classification of a restricted number of TC configurations considered by SIDE. These configurations are discussed in more detail as follows.

The main subdivision of transformer groups is made according to the switching and insulation coordination requirements such that it is possible to distinguish TC groups equipped only with disconnectors, those having one input or output circuit breaker as well as those containing circuit-

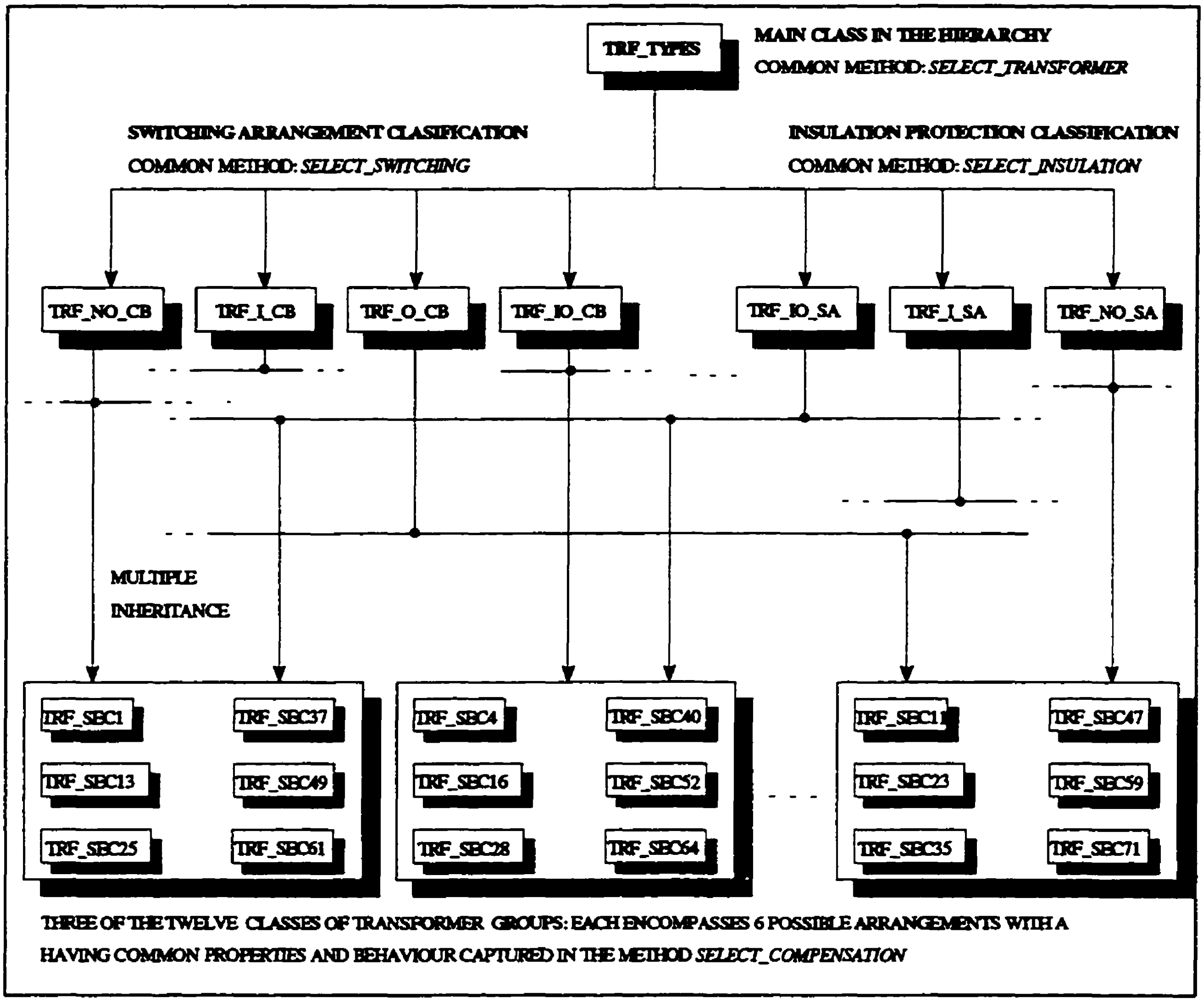

Figure 3.11: Classification of substation transformer groups.

breakers on both sides of the transformer. Normally, circuit breakers are not installed if the chosen busbar arrangements possess sectionalizing breakers. For example, when double busbars with sectionalizing breakers are employed at both the high-voltage and low-voltage sides of the substation, circuit breakers are not necessary since busbar sectionalizing breakers provide enough facilities to perform the necessary switching. However, if a busbar arrangement without sectionalizing breakers is used at either, the high-voltage or low-voltage side of the substation, a circuit breaker must be furnished at the transformer terminal that has no sectionalizing breaker.

As far as internal insulation is concerned, the power transformer may be protected by surge arresters on both sides or only on the high-voltage side or not at all depending on the environmental conditions (indoor/outdoor substation) and on the voltage level. Thus, for outdoor substations, surge arresters on both sides are required to protect against lightning strokes. Moreover, for voltages above 245 kV, the presence of surge arresters is recommended in order to protect against switching overvoltages. Therefore, there exist four possible subdivisions according to the switching requirements which, when combined with the three basic subdivisions due to insulation protection requirements, make up the twelve main classes of TC groups (Figure 3.11). In addition, each of these twelve classes is further subdivided according to the compensation and fault protection tasks accomplished by these TC groups. Hence, some TC configurations contain SVC or capacitor banks connected at the transformer tertiary winding, others may have a grounding transformer to provide a path for zero-sequence currents or an auxiliary supply unit. Consequently, seventy two TC arrangements have to be considered in the SIDE knowledge base.

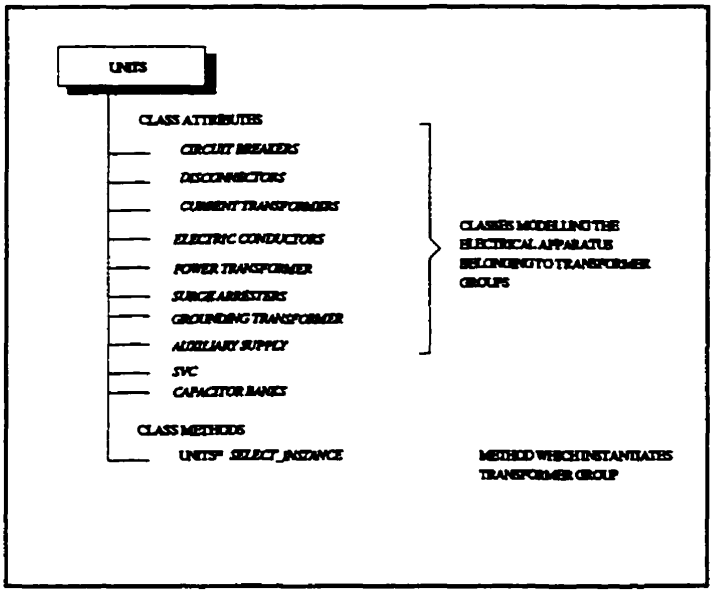

Figure 3.12: Transformer group class structure.

The object-oriented knowledge model of TC groups is the most complex of the substation composite parts. It consists of the main class "Units" representing an object-oriented interpretation of a transformer group (Figure 3.12) and one class hierarchy (Figure 3.11) where the above-discussed TC group arrangements are classified. Since the number of arrangements is fairly large, the hierarchical class organization takes advantage of all available object-oriented mechanisms such as inheritance, multiple inheritance and polymorphism [Boo91]. Thus, as presented in Figure 3.21, the two subdivisions, according to the type of switching and insulation protection, are realized through twelve main sub-classes. For example, the class "TRF_IO_SA" encompasses all arrangements having surge arresters at both the input and output sides of the transformer, while the class "TRF_I_CB" contains those arrangements equipped with a circuit breaker at the transformer high-voltage terminal. Accordingly, the arrangement having both characteristics (e.g. class TRF_SEC1 in Figure 3.21) , i.e. two surge arresters and no circuit breakers, must inherit properties from both classes "TRF_IO_SA" and "TRF_NO_CB" which in turn inherit from the class on top ("TRF_Types"). The mechanism of multiple inheritance assures that properties of the "TRF_Types" class are not inherited twice (through "TRF_IO_SA" and "TRF_NO_CB" classes) by the class "TRF_SEC1".

The properties of the class "TRF_Types" are methods that perform the instantiation of electrical apparatus. In addition, this class contains two important methods, namely, "SelectEquipment" and "SelectTransformer". The former method which represents an excellent example of polymorphism, invokes in its body the methods which take care of power transformers ("SelectTransformer"), insulation protection ("SelectInsulation"), switching ("SelectSwitching") and compensation equipment ("SelectCompensation"). The method ("SelectTransformer") instantiates the power transformer as the main and indispensable component of TC groups and, as such, is defined as a member of the top class and is inherited by all sub-classes in the hierarchy. The methods "SelectSwitching" and "SelectInsulation" contain the knowledge managing switching and insulation requirements for different switching and insulation groups. Thus, these methods are defined as properties of the twelve main subclasses which model different switching and insulation arrangements.

For example, the method "SelectSwitching" from the class "TRF_I_CB" would know that the instance of any of its sub-classes must possess one circuit breaker at the input side while the same method defined in "TRF_IO_CB" class would arrange the instantiation of circuit breakers at both sides of the transformer. Finally, the methods "SelectCompensation" are defined at the lowest level in the hierarchy, i.e. in every single sub-class modeling one particular TC arrangement. For example, the instantiation of the power transformer of the class "TRF_SEC49" is performed by the method "SelectTransformer" inherited from the top class "TRF_types", the instantiation of switching equipment is accomplished through the method "SelectSwitching" inherited from the class "TRF_NO_CB" (no breakers), the surge arresters are defined by the method "SelectInsulation" from the class "TRF_IO_SA" while the instantiation of the shunt capacitor bank is carried out by the method "SelectCompensation" which is uniquely defined inside the class ("TRF_SEC49") itself. The mechanism of polymorphism is efficiently implemented here through the method "SelectEquipment" which is inherited by all classes in the hierarchy but performs different tasks. The task distinction is explicit in the methods "SelectSwitching", "SelectInsulation" and "SelectCompensation" which instantiate different electrical equipment in different classes and are all invoked inside the body of "SelectEquipment".

The properties of the class "Units" (Figure 3.12) are also class models of electrical apparatus which belong to the TC groups (class models for circuit breakers, disconnectors, capacitor banks, power and instrument transformers and surge arresters). In addition, the method "TRFSelectInstance" contains knowledge processed when new instances of the class "Units" (as shown in Figure 3.12) are to be created. This instantiation process is accomplished as follows.

Given the substation single-line-diagram as an input argument, the method "TRFSelectInstance" first identifies which TC group arrangement is to be implemented in the selected single-line-diagram. The "TRF_Types" class hierarchy is then searched in order to locate the appropriate class which models this TC arrangement. The instantiation of this class is then performed by calling upon its method "SelectEquipment" whose execution results in the construction of the electrical equipment pertinent to this particular TC group arrangement. This TC groups instantiation process is then repeated for all TC groups in the single-line-diagram.

One example of TC group instantiation is as follows. Suppose that the single-line-configuration of the desired transformer group conforms to the class "TRF_SEC_1". The switching equipment pertinent to this class consists only of input and output disconnectors. The insulation protection is accomplished by surge arresters placed on both sides of the transformer while neither compensation nor grounding transformers are needed. Thus the class "TRF_SEC1" is located first by the method "TRFSelectInstance". The method "SelectEquipment" which belongs to the class "TRF_SEC1" is then processed as follows: (i) the power transformer is created first through the method "SelectTransformer", (ii) the method "SelectSwitching" is invoked next in order to instantiate input and output disconnectors, (iii) the input and output surge arresters are constructed by the method "SelectInsulation", (iv) finally, the method "SelectCompensation" is called upon but it does not instantiate any electrical apparatus since its definition in the class "TRF_sec1" contains an empty body (no compensation or special protection is provided in the arrangement modeled by "TRF_SEC1"). The object created by the method "SelectEquipment" is an instance of the class "Units" which, in this example, has two objects modeling disconnectors, two objects representing surge arresters and one object modeling the power transformer. Note that the power transformer represents a complex electrical apparatus containing two current transformers which are instantiated as part of the power transformer class. In a similar fashion, all the other TC groups can be instantiated as required.

3.5 Design Specifications in SIDE

The design specifications in SIDE represent the basic inputs imposed on the substation design process by the power system, the environment and by reliability requirements. These specifications are known to power engineers as *design criteria* and are here categorized as follows:

Power System Criteria include system-dependent parameters such as rated voltage levels, load ratings, short-circuit and insulation levels in the existing network, data related to the incoming and outgoing power lines as well as data regarding reactive compensation.

The specified values for voltage levels are the maximum operating voltages for equipment. The information regarding load rating (MVA) is provided in two forms: a total peak load rating of a substation and as a set of peak load ratings separately characterizing each customer supplied by the substation. The network short-circuit levels are specified by two parameters, namely, the three-phase and single-phase short-circuit capacity (kA). The inputs used for insulation coordination purposes are the expected slow-front and temporary overvoltages as well as the specified risk of failure of the insulation [IEC71]. The incoming and outgoing line parameters are line related (the line capacity and nominal rating, the type of the conductor, the failure and repair rates, the line length) and non-line related parameters (type of measurements required, type of communication facility). The data regarding reactive power compensation refer mainly to the type and ratings of the static VAR systems usually implemented in the high voltage part of the substation. Since substations, in general, operate at several voltage levels, it is important to mention that most of the above-described input data have to be specified for each voltage level.

Environmental Criteria characterize typical environmental conditions which may have a strong impact on the substation design such as ambient temperature range, altitude above sea level, wind velocity, ice loading, rainfall, snow, pollution levels, audible noise level and the location of the substation (indoor or outdoor).

Reliability Criteria represent the most important factors which impact the selection of substation single-line diagram alternatives. These are purely deterministic criteria given in the form of a specified list of credible events and possible consequences. Credible events could be component faults or failures, scheduled outages or combinations of these. The possible consequences following a credible event are the disconnection of one or more components in the substation possibly leading to load curtailment. A possible list of credible events is [Sub90]:

- One circuit-breaker out of service followed by a line fault (CBOOS + LF).
- Line fault plus breaker failed to trip (LF + BFT).
- Breaker out of service plus line fault with breaker failed to trip (CBOOS+LF+BFT).
- One breaker out of service plus breaker fault (CBOOS+BF).
- One bus out of service plus breaker fault (BUSOS+BF).
- One bus out of service plus line fault (BUS)S+LF).
- Two buses faulted simultaneously (2BUSF).

The considered potential consequences resulting from the aforementioned credible events are listed below in order of decreasing severity:

- Complete substation outage (All Lines)
- Two parallel lines out + one series line out (2PARL+1SERL)
- Two parallel lines out (2PARL)
- Two series lines out + tie-line out (2SERL+TIEL)
- Two series lines out + station split (2SERL+ST_SPLIT)
- Two series lines out (2SERL)
- One line + tie-line out (1LINE+TIEL)
- One line out + station split (1LINE_+STSPLIT)
- One line out (1LINE)
- Station split (ST_SPLIT)

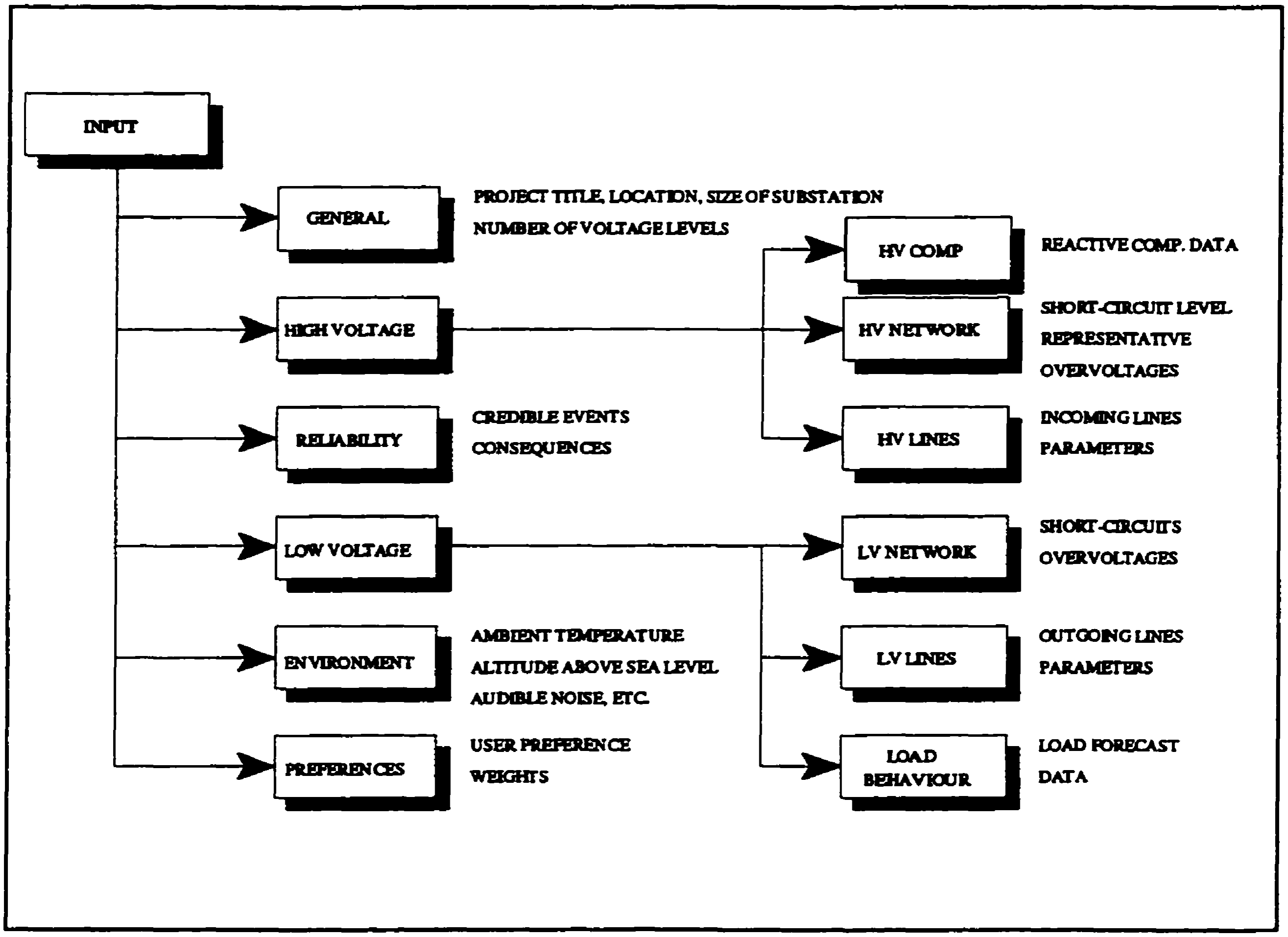

Figure 3.13: Design specifications class structure.

Note that the term "series line" can refer to any two lines connected in series within the substation. A similar comment applies to the term "parallel lines". Finally, the terminology "tie-line" denotes a branch connecting two bus-bar subsystems.

Apart from the above mentioned design criteria, there exists another set of input specifications, namely, a set of *user preference weights* representing the user preferences which the designer wishes to assign to the four basic design performance criteria. These criteria are Cost, Reliability, Operational Flexibility and Impact on the Environment. The specified weights are used as inputs to a multi-criteria analysis [Mas88] to help choose preferred substation single-line configurations and some types of equipment. In addition to these design performance preferences, the designer is allowed to specify a limit on the number of design alternatives generated by SIDE.

The design specifications of a substation form a complex structure. The input design parameters can be classified into several groups according to common characteristics (power system criteria, environmental criteria, reliability criteria, design performance preferences). Furthermore, for each group, the data must be specified for each voltage level in the substation. Accordingly, the object-oriented design specification class structure shown in Figure 3.13 has been developed to model the complex structure of the specifications of a substation:

The basic design specification class "Input" consists of the following class Members: "General", "High-voltage", "Low-voltage", "Reliability", "Environment" and "Preferences". These classes are now discussed in greater detail.

The class "General" contains some general information about the design project such as its title, the location of the substation, the type of substation and data related to the financing of the project. It also contains information related to electric properties including the total power rating and nominal voltage levels.

The class "High-voltage" represents the specifications related to the high-voltage part of the substation. It consists of classes which model previously discussed power system criteria ("HV_Network"), incoming line data ("HV_Lines") as well as reactive power compensation data ("HV_Comp").

The "Low-voltage" class models power system criteria and line data related to the low-voltage parts of the substation. In addition, it contains the class "Load-Behaviour" which contains classes corresponding to different types of loads such as residential, industrial, commercial and institutional. The attributes of each of these classes are the power consumption at different time stages of implementation as well as data describing the cost of interruptions [Bil87].

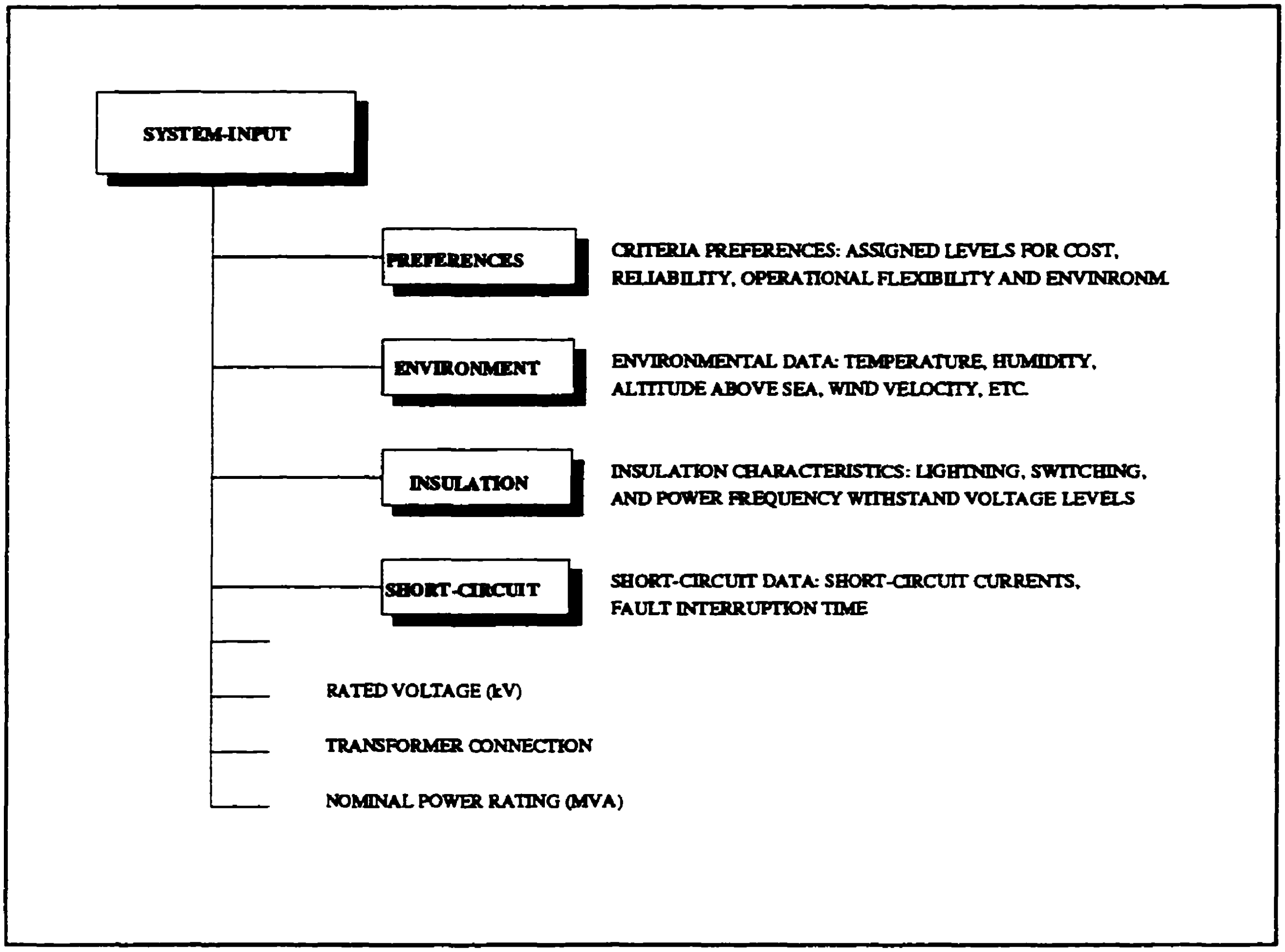

Figure 3.14: The "System_Input" class structure.

The attributes of the "Reliability" class are the specified credible events and potential consequences as discussed previously in this section. The class "Environment" encompasses the relevant environmental data (e.g. climatic conditions, altitude, perscribed levels of audible noise and expected air pollution levels). Finally, the class "Preferences" models the design preference weighting factors discussed earlier.

Apart from its properties, each class also contains a set of methods which manipulate these properties. There exist two types of methods, namely, those which handle database management tasks and those which perform the instantiation of input classes. The former control the copying, deletion,

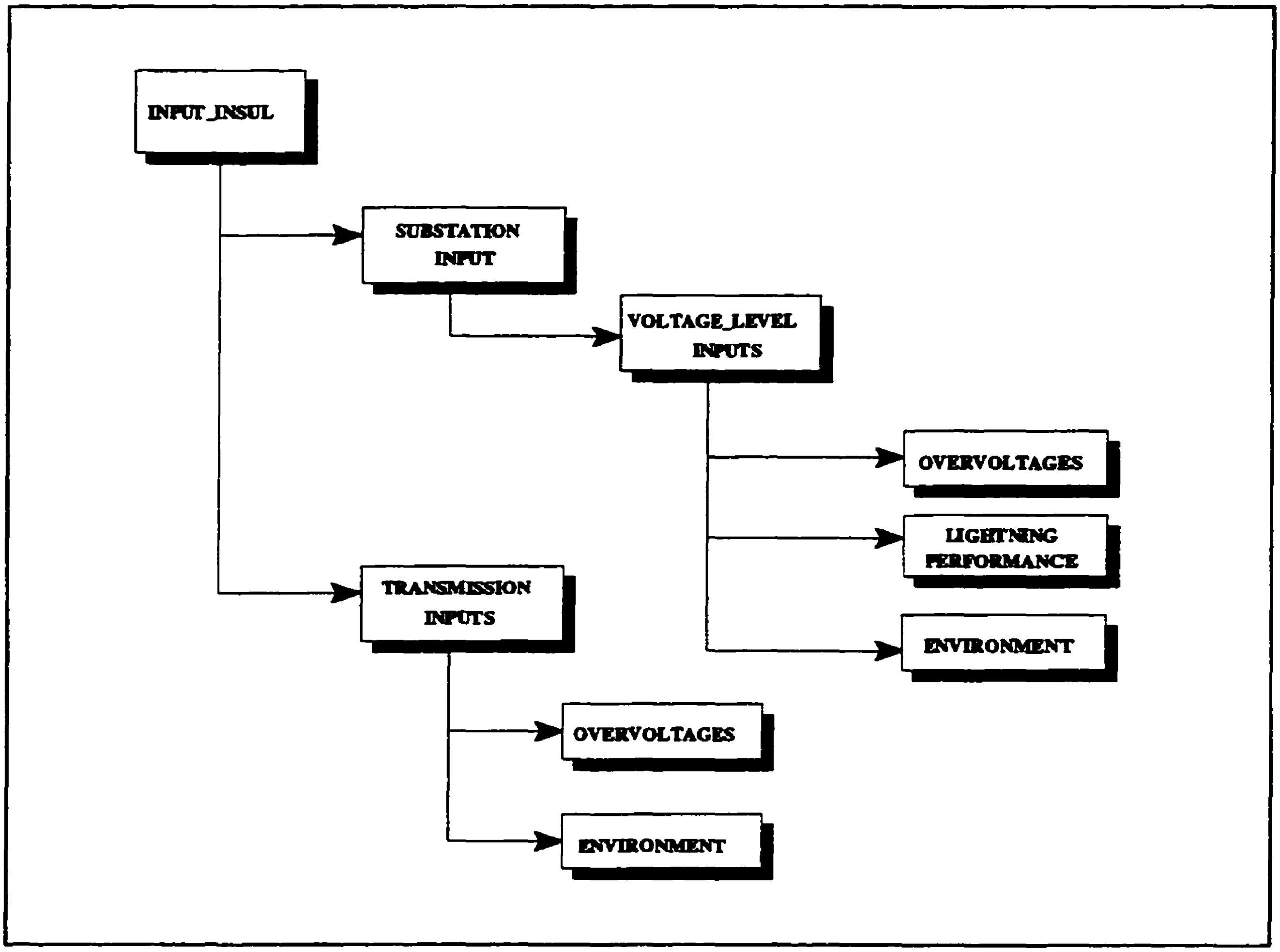

Figure 3.15: "Input_Insul" class structure.

addition and modification of input records, while the latter contain rules which distribute the input data (entered through the graphical user interface) over the corresponding input classes (Figure 3.13).

Figures 3.14 and 3.15 describe two auxiliary input classes dynamically created from the main input classes described above. Their purpose is to avoid passing the entire input class to frequent tasks which only require a limited subset of input data. Such tasks are the equipment selection process and the simulation procedures. The auxiliary input classes are "System-Input" and "Insul-Input".

The properties of the class "System_Input" shown in Figure 3.14 are the nominal voltage and power ratings, the short-circuit network parameters, slow-front and temporary overvoltages, environmental data and the user preference weights. Once constructed at the beginning of the design process, the instance of the "System_Input" class is used as an input parameter in the electrical apparatus class constructors and remains active until the last piece of substation equipment has been constructed.

The "Input_Insul" class is another sub-group of the main design specifications and models the input data related to the insulation coordination process. It uses the information related to the temporary and slow-front overvoltages as an input to its constructor. Since these data are provided as part of the general input specification class "Input", the instance of that class is passed as an argument to the constructor of the "Input_Insul" class. The organization of the "Input_Insul" class is displayed in Figure 3.15. It has two main class members, namely, "Substation_Input" and "Transmission_Input". The former contains input data used in the insulation coordination of substations while the latter models inputs related to the transmission line design. Note that the insulation coordination simulation tool is intended to be used as a general supporting expert system in the power system design area and not just as a module of the substation design system, SIDE [Ata95-1]. The "Substation_Input" class has the class member: "Voltage_Level_Inputs" which, in turn, contains the class "Overvoltages". This class captures information about slow-front and temporary overvoltages at each substation voltage level. The class "Substation_Environment" which models environmental conditions contains information about levels of pollution, separation distances of surge arresters and the specified risk of failure. The class "Lightning_Performance" contains information regarding the type of line or the line outage rate required to find representative fast-front overvoltages for the equipment [Bel96-1]. Once constructed, the instance of the "Input_Insul" class is used as an input to the insulation coordination simulation process and is destroyed as soon as the insulation coordination simulations are completed.

3.6 Simulation Procedures

As stated previously, two kinds of knowledge are found in SIDE, heuristic and procedural. The procedural knowledge is generated by and present in various simulation tools. These simulation tools are activated at different stages of the design. They include short-circuit analysis, insulation coordination, preliminary analysis of transformer units, reactive power considerations, mechanical stress analysis, cost evaluation, reliability evaluation and multi-objective comparison of design alternatives. The results of these analyses are used when selecting the substation electrical equipment and single-line-diagram, as well as when comparing different final design alternatives.

The object-oriented model of the simulation knowledge in SIDE is shown in Figure 3.16. The class "Simulations" encompasses all results and procedures related to the above-mentioned simulations. Its class members are "Short-Circuit", "Insulation", "Transf_Analys", Reac_pow", "Mech_Stress", "Reliability", Multi_obj" and "Cost" which model the corresponding simulation activities. In addition to the simulation results, the methods of these classes contain the necessary procedural knowledge to generate these results.

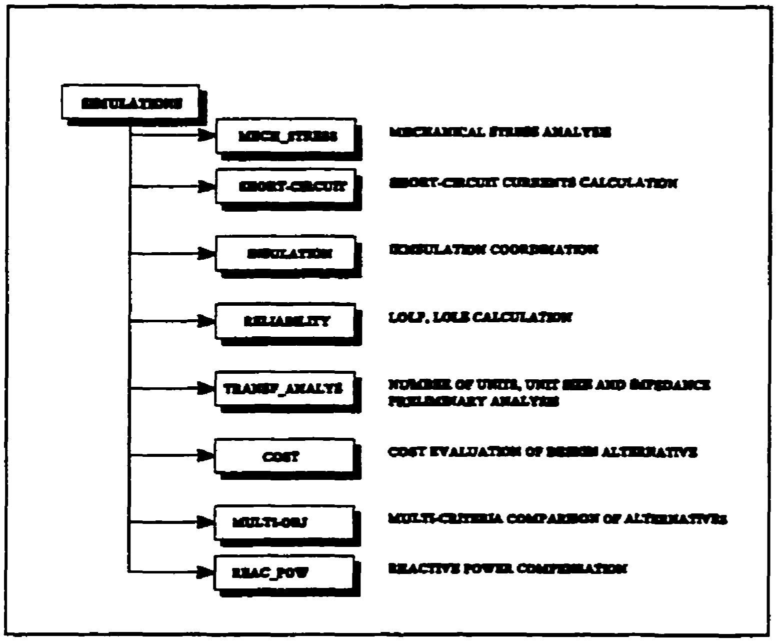

Figure 3.16: The "Simulation" class.

The following subsections describe in more detail each of the above-mentioned substation simulation activities.

3.6.1 Short-circuit Analysis

Short-circuit studies are one of the most important simulation activities in substation design providing the necessary information for the equipment selection and protection system design. The input data consist of the high-voltage network positive and zero-sequence Thevenin impedances as well as preliminary information about transformer units such as impedances, number of units and type of winding connection (will be discussed later in Section 3.6.3). The objective of short-circuit analysis is to determine values of short-circuit currents at important locations in the substation. There are basically two kinds of short-circuit faults which are considered, namely, three-phase-to-ground and single-phase-to-ground faults. When dimensioning HV and LV electrical equipment, the short-circuit values are calculated assuming that the fault occurs at the substation high and low-voltage busbars since these types of faults are considered to be the most severe. As for protection design, short-circuit studies must be carried at other locations in the substation, including the calculation of minimum fault currents.

Two basic quantities are normally determined from short-circuit studies, namely, the *short-circuit fault current* and the *short-circuit peak current* as follows:

High-voltage side:

$$I_1 = 3*V / (2*Z_1 + Z_0) + I_{sc1} \qquad (3.1a)$$

$$I_3 = V / Z_1 + I_{sc3} \qquad (3.1b)$$

where I_1 and I_3 are respectively the single-phase and three-phase short-circuit currents in kA , V is the rated phase-to-ground voltage at the HV side of the substation and Z_1 and Z_0 are the positive and zero-sequence equivalent impedances of the network as seen from the high-voltage bus. The terms I_{sc1} and I_{sc3} represent the short-circuit contributions from other substations to which the substation is connected.

Low-voltage side:

$$I_1 = 3 * V \, / \, (2 * Z_1 + Zo)$$
$$I_3 = V \, / \, Z_1 \tag{3.2}$$

where Z_1 and Z_0 are the positive and zero-sequence equivalent impedances of the network as seen from the low voltage bus and V is the rated phase-to-ground voltage at the LV side of the transformer.

The peak values of the short-circuit currents are also needed for the calculation of mechanical stress on electrical equipment. These peak values are determined according to the following equations:

$$\begin{aligned} Ip_3 &= k * \sqrt{(2)} * I_3 \\ Ip_1 &= k * \sqrt{(2)} * I_1 \end{aligned} \tag{3.3}$$

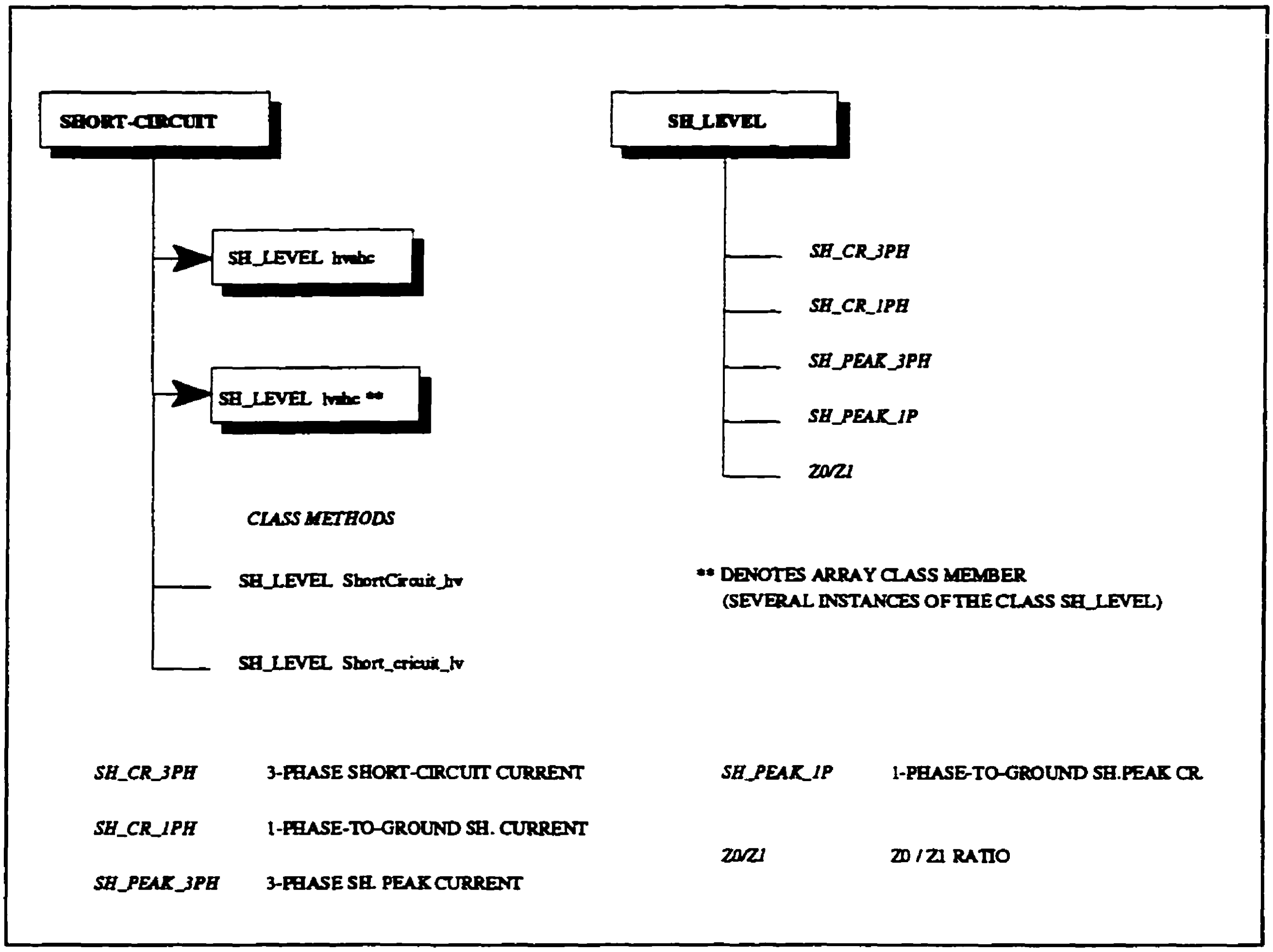

Figure 3.17: Short-circuit simulation model.

where Ip_3 and Ip_1 denote the three-phase and single-phase-to-ground short-circuit peak currents respectively, while k is a parameter which depends on the ratio X / R where X and R designate the total reactance and resistance from the source of supply to the fault location. The factor k takes values in the range of 1 to 2 [ABB88].

Another important quantity to consider in short-circuit analysis is the ratio Z_o / Z_1. If this ratio is greater than 1 the three-phase fault can be considered as the most critical type of fault producing the largest value of short-circuit current. However, if this ratio is less than one, the single-phase-to-ground fault is considered the most critical.

SIDE models the knowledge associated with short-circuit analysis as depicted in Figure 3.17. The "Short-Circuit" class which is a member of the main "Simulations" class, has one array class member "SH_Level" which is instantiated for each voltage level. Its properties, as seen in Figure 3.17 represent the aforementioned short-circuit analysis parameters. Two methods are contained in the "Short-Circuit" class, namely, Short-circuit LV and Short-circuit HV which instantiate the corresponding SH-Level classes through the knowledge described by equations 3.1 to 3.3 and other heuristic rules (e.g. type of transformer grounding).

3.6.2 Insulation Coordination

The task of insulation coordination is to select the electric strength of equipment in relation to the voltages which can appear in the system taking into account the environment in which the equipment operates and the characteristics of the available protective devices (e.g. surge arresters) [IEC71]. The detailed description of the insulation coordination process as well as the outline of the proposed object-oriented supporting expert system [Ata94, Bel96-1] for insulation coordination in power system design (ICES) are provided in Section 2.3.4 of Chapter 2. The subject of the current section is to show how ICES can be integrated with SIDE in order to generate the standard withstand voltage levels for the selection of substation equipment.

Figure 3.18 outlines the structure of two main classes developed to interface with the supporting expert system for insulation coordination, ICES. Thus, the class "Insulation" which is a member of the main "Simulations" class contains the following attributes:

- *Protected_hv* modelling insulation characteristics of protected equipment at high voltage.

- *Unprotected_hv* modelling insulation characteristics of unprotected equipment at high voltage.

• *Protected_lv* modelling insulation characteristics of protected equipment at low voltage.

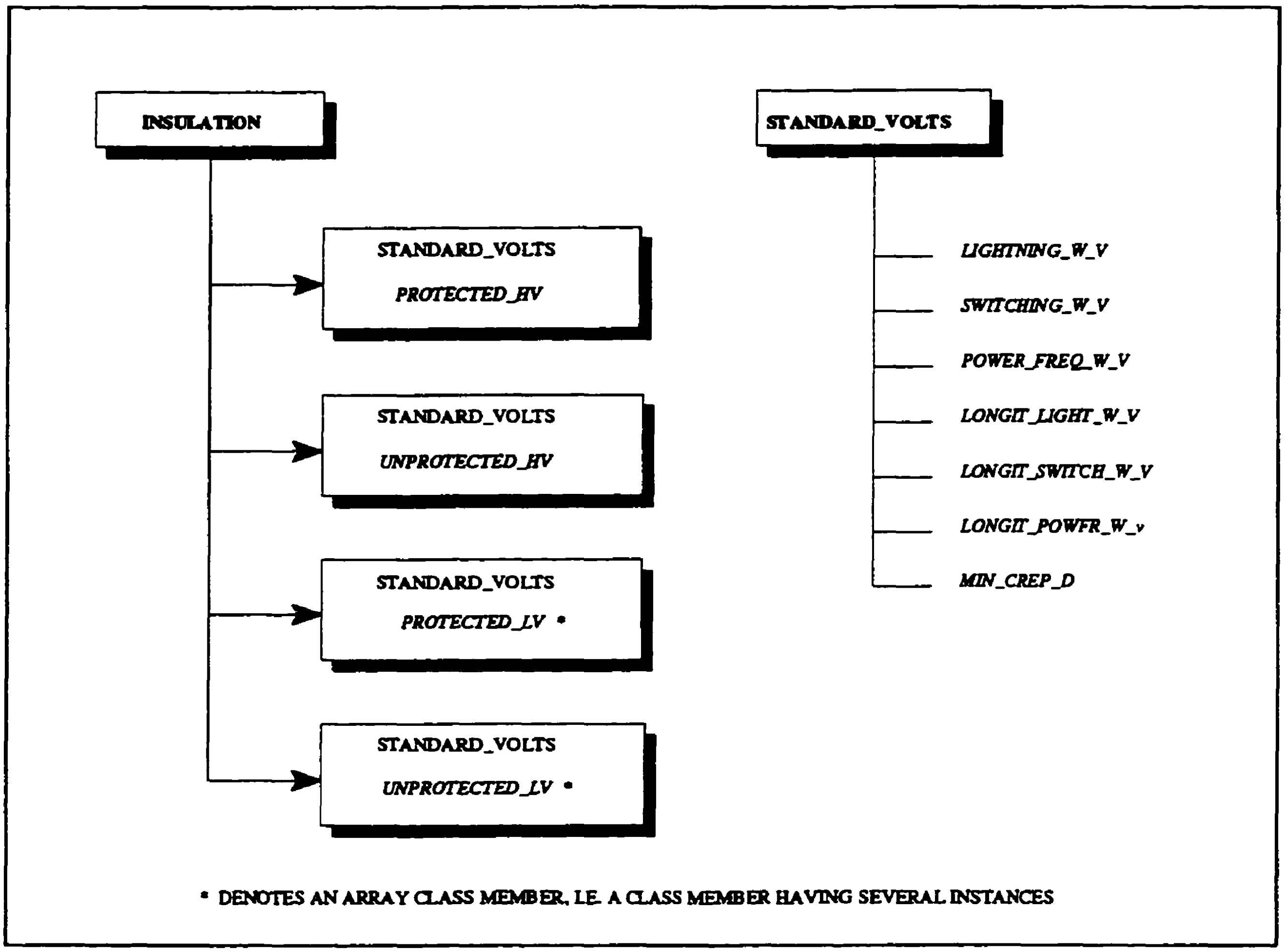

Figure 3.18: The substation insulation coordination class model.

• *Unprotected_lv* modelling insulation characteristics of unprotected equipment at low voltage.

The above four attributes are instances of the class "Standard_Volts". Note that there may exist several instances of *Protected_lv* and *Unprotected_lv* since there may be several low-voltage levels in the substation.

As shown in Figure 3.18, the attributes of the class "Standard_Volts" are two sets of standard withstand voltage levels , namely, phase-to-ground and longitudinal, covering lightning, switching and power frequency overvoltages. These attributes are assigned the appropriate values from the supporting expert system ICES as follows:

The constructor of the class "Insulation" receives, as input argument, an instance of the class "Input_Insulation" (see Section 2.3.4) which contains all input information necessary to perform insulation coordination (e.g., slow-front and temporary overvoltages and environmental conditions). The supporting expert system ICES is then activated through the execution of the constructor of the class "Design_Shell" (Figure 2.10, Chapter 2) thus creating an instance of this class containing all results of the insulation coordination process. The Design-Shell attributes "Protected_Insulation" and "Unprotected_Insulation" are then accessed by the constructor of the class "Standard_Volts". This is done in order to instantiate the class "Standard_Volts" for each type of electrical equipment (protected, unprotected) and for each voltage level in the substation, thereby providing standard withstand voltage levels for the substation electrical equipment.

In summary, the insulation coordination activity in substation design is carried out in two major steps. The first step is the execution of the supporting expert system which actually performs the insulation coordination exercise while the second step constitutes the transferring of the results obtained at the first step to the "Simulations" class which belongs to the substation design tool. It is important to remember that the insulation coordination domain knowledge is not an intrinsic part of the substation design knowledge-base but is, rather, modelled independently and constitutes a separate supporting expert system. This is consistent with the intended purpose of the supporting expert systems which are independent tools called upon only when needed. Thus, the only problem which emerges as far as supporting systems are concerned is related to their communication with the various main knowledge-based systems. One example of such a communication interface has been presented above for the case of insulation coordination in substation design.

3.6.3 Preliminary Analysis of Transformer Units

Preliminary transformer unit analysis is a very important activity usually performed at the beginning of the substation design process. It consists of defining the number of units, their approximate ratings, the number of on-load taps and the transformer leakage impedances. These data are important for several other simulation activities such as short-circuit analysis and reactive power consideration. In addition, the number and size of transformer units can influence the selection of the substation single-line diagram.

The selection of the number of transformer units is based on the N-1 criterion which states that the failure of any one component must not cause load curtailment. This criterion results in the following formulae:

$$N = \text{int}\,[P_{tot} / P_u] + 1 \tag{3.4a}$$

$$P_u = \text{int}\,[P_{tot} / (N-1)] \tag{3.4b}$$

where N denotes the number of transformer units, P_{tot} is a total power to be supplied and P_u is the selected transformer rating. The function "int" rounds up the fraction P_{tot} / P_u to the next higher integer. Although the above equation accounts for the N-1 criterion, it is obvious that it cannot be used to calculate the number of units unless the selected transformer rating is also known. On the other hand, the selection of P_u depends not only on the ultimate load of the substation but also on the load levels at different stages of implementation (reflected in the value of P_{tot} over the years). Thus, the process of selecting the number and the rating of transformer units is as follows:

(A) Adopt a per unit level of surplus transformer capacity (the difference between the total transformer power capacity and the total load) and select the number of transformer units from Table 3.2. Note that the values provided in Table 3.2 are obtained from the transformer surplus condition which can be mathematically expressed by the following inequality:

$$N * P_u - P_{tot} \leq x * P_{tot} \tag{3.5}$$

Table 3.2: The number of units vs transformer capacity surplus relationship.

Number of Units, N	2	3	4	5	6	7	8 ...
Surplus, x (%)	100	50	33	25	20	16	14 ...

where x denotes the transformer capacity surplus expressed as a percentage of the total load of the substation. For example, if it is desired that the total transformer capacity should be not higher than 33% of the total load, and the N-1 criterion must also be met, it follows that the station must have four transformer units. If, on the other hand, a surplus of 50% is chosen, the number of units required reduces to three. Thus, it can be observed, that the N-1 criterion imposes higher surpluses when fewer units are chosen. An important design consideration is therefore whether it is preferable to have fewer units and higher surpluses or the inverse. The choice of fewer units and higher surpluses is then the preferred one if the cost of the higher transformer capacity surplus is lower than the cost of adding a new unit and lowering the capacity surplus. The cost of transformer capacity depends on the type and location of the transformer and especially on the voltage level.

(B) Examine the configuration with the number of units equal to one less than the number selected at step (A) by comparing the incremental costs of more units and less surplus versus fewer units and more transformer capacity surplus. Repeat until no further cost improvement is possible.

(C) Having obtained the number of units from the previous steps, the unit rating is found from equations 3.4a and b.

(D) Once the number and rating of transformer units has been determined, there remains to define two other important characteristics, namely, the transformer leakage reactance and the number of on-load taps to control the secondary voltage. The former is found using Table 3.3 shown below which suggests a relation between the transformer leakage reactance and typical rated voltages[1]. Note,

Table 3.3: Transformer leakage reactance vs rated voltages.

Voltage [kV]	765/330	765/245	765/120	330/120	330/25...	120/25...
Impedance [%]	12	12	18	20	25...	10 ...

however, that the value of the transformer reactances may have to be higher than those suggested in Table 3.2 whenever short-circuit studies reveal that the fault current exceeds the standard low voltage breaker interruption capacity. In such a case, it is more economical to increase the transformer reactance (thus lowering the fault current) than to install a more costly circuit breaker with a higher interruption capacity.

(E) The number of taps as well as their settings are determined such that the voltage at the transformer secondary side can be maintained over the loading cycle of the substation with a maximum variation of 10% in the primary voltage. The number of taps is estimated through the following steps:

> Given the real and reactive load of each transformer as well as the transformer impedance, the value of reactive loss in the transformer is approximately,

[1] This table is based on discussions with experienced planners and existing design manuals [ABB88].

$$Q_{Loss} = (S_L \ / \ E)^2 \ * \ X_t \tag{3.6}$$

where S_L is the transformer load in MVA and X_t the transformer impedance. The quantity E is the rated phase-to-phase secondary voltage.

Thus, the MVA load at the transformer primary side, S_p, is given by,

$$\begin{aligned} S_p &= \sqrt{P_L^{\,2} + Q_p^{\,2}} \\ Q_p &= Q_L + Q_{Loss} \end{aligned} \tag{3.7}$$

The voltage drop, dE , as well as the required regulation $(dTAP)_{\%}$ will be approximately given by:

$$\begin{aligned} (dE)_{\%} &= (S_p \ / \ S_L - 1) \ *100 \\ (dTAP)_{\%} &= (dE)_{\%} + 10 \end{aligned} \tag{3.8}$$

Finally, the number of required taps is determined as,

$$\begin{aligned} &TotalTaps = integer(dTAP_{\%} \ / \ 2.5) \\ &TapsDown = 2 \\ &TapsUp = TotalTaps - TapsDown \end{aligned} \tag{3.9}$$

where TotalTaps is the total number of tap-changing positions, TapsDown is the number of positions intended for voltage decrease (fixed to 2 since the upper voltage limit is just 5% = 2x2.5% above the reference value of 1 p.u.) while TapsUp denotes the number of taps used to increase the voltage.

The knowledge related to the preliminary transformer analysis is modelled by a class structure "Trf_altr" which is a part of the class "Simulations". As shown in Figure 3.19, this class contains several members of the type "Trf_LV" modelling transformer units at different low voltage levels (e.g.

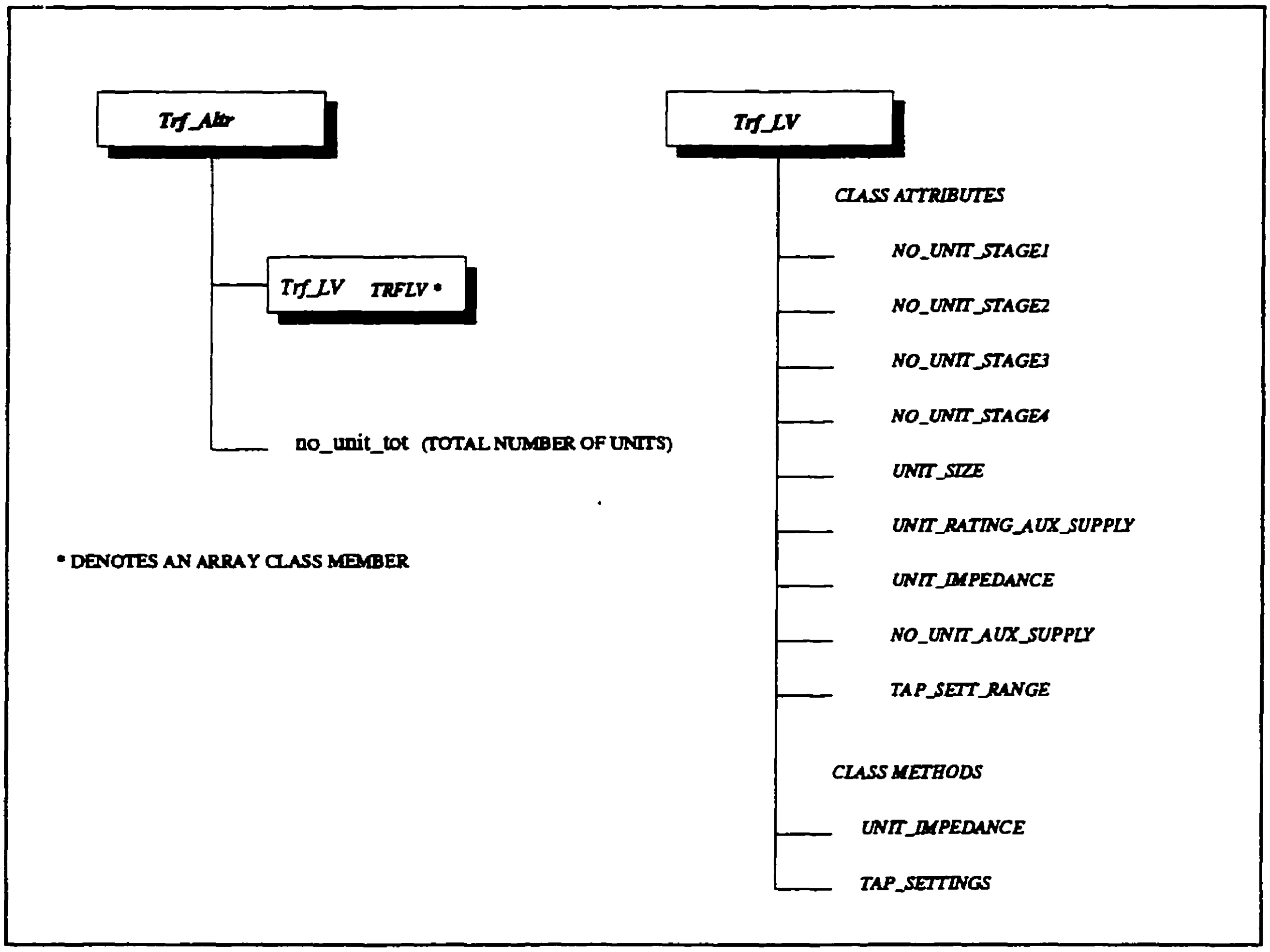

Figure 3.19: Transformer preliminary analysis class model.

765/330 and 765/230 kV). In addition, "Trf_Altr" contains a member *no_unit_tot* which represents the total number of transformer units in a substation. The properties of the class "Trf_LV" are the above-described basic transformer characteristics such as transformer rating, leakage impedance as well as the tap changer parameters. This class also preserves information about the number of units at different stages of implementation. Two methods belonging to the class "Trf_LV", namely, *UnitImpedance* and *TapSettings* perform the selection of impedance and tap changer characteristics (using the knowledge described above) when called upon by the "Trf_LV" class constructor. The selection of the rating and the number of units is accomplished directly in the "Trf_LV" class constructor rather than through a separate method.

3.6.4 Reactive Power Considerations

Reactive power management in a substation can be subdivided into activities at the high and low voltage levels.

The required reactive power management activities at the HV side are: Voltage regulation, reduction of overvoltages, damping of subsynchronous oscillations, reduction of voltage or current unbalance and improvement of steady-state and dynamic stability. Static Var systems (SVS) are usually implemented to provide continuous and fast control of voltage at a given location. Since the specification of static Var systems requires detailed knowledge of the network, this step is not usually carried out in the substation design process but is, rather, performed as part of system studies. Therefore, all data concerning the application of SVS on the high-voltage side of the substation must be provided as part of the design input specifications.

At the low-voltage side, the most frequent reactive power control activity is power factor improvement. This is accomplished through shunt capacitor banks or SVS. Capacitor banks are employed mainly in distribution and subtransmission substations (voltage levels up to 315 kV) when rapid and continuous reactive power control is not required. The selection of capacitor banks is made such that voltage variations remain with a prescribed range (e.g. 3 %). Consequently, for a 3% range, the maximum MVA of shunt capacitors that can be switched at one time is $0.03*(MVA)_{SC}$ where $(MVA)_{SC}$ is the three-phase short-circuit MVA at the capacitor location.

Static Var systems are implemented mainly in subtransmission and transmission substations, particularly if smooth and fast voltage control is required, but their specification represents a more complex exercise than capacitor banks. For voltages up to 25 kV, compensation equipment is almost exclusively connected at substation busbars. For higher voltage levels, the connection is often accomplished at the tertiary winding of power transformers.

The above general discussion has introduced two main approaches to realizing reactive power management, namely, using SVC or using shunt capacitor banks. These are now discussed in more detail.

Shunt Capacitor Banks. In order to design the reactive power compensation system using shunt capacitor banks, one must determine the following quantities:

(a) The required amount of reactive power. The total amount of reactive power the compensation system must generate can be determined from the reactive power losses in the transformers (as discussed before) and the reactive component of the load.

(b) The number and the rating of capacitor banks. The capacitor units are standardized in terms of their ratings and the total rating of one switched capacitor bank depends on the short-circuit power as discussed earlier. Depending on the voltage level in the substation, there exist several possible choices for capacitor bank according to their MVar ratings. Table 3.3 [ABB88, HQM], summarizes the data regarding available shunt capacitor banks configurations. In this Table, Qmax and Qmin are the maximum and minimum amounts of reactive power that the capacitor bank can generate, ΔQ denotes the amount of MVars by which two successive bank ratings belonging to the same voltage group differ, while Qunit is the reactive power capability of one single unit (banks are usually made of chains of units). For example, when banks belonging to the 145 kV voltage group are considered, the firstbank on the list is the one with the minimum reactive capability equal to 15 MVar

Table 3.4: Characteristics of shunt capacitor banks [ABB88, HQM].

Voltage [kV]	< 72.5	< 145	< 245	< 330
Qmax [MVar]	12	67.5	108	205
Qmin [MVar]	6	15	36	65.4
ΔQ [MVar]	3	7.5	18	34.2
Qcan [MVar]	0.5	0.5	0.5	0.5
Reliability Factor	0.65	0.75	0.85	1

(column 2, Table 3.4). To obtain the next standard MVar rating corresponding to the 145 kV, the step value of ΔQ=7.5 MVar is added to the Qmin and the calculated rating is equal to 22.5 MVar. According to Table 3.3 there exist several possible ways to select the number and the rating of capacitor banks. Thus, for a given voltage level, one can select fewer capacitor banks with higher reactive capability or a larger number of banks having a lower reactive power rating. Obviously, the larger number of banks establishes the more reliable configuration entailing, on the other hand, a higher cost of installation. Similarly, as far as operational flexibility is concerned, it is possible to conclude that the more banks installed, the better the flexibility achieved. In addition, if environmental considerations are introduced (e.g audible noise) the problem of selecting the number and rating of capacitor banks could be considered as being a multi-criteria optimization task [Mas88] as discussed in Section 1.5. Multi-criteria analysis is followed here since the above-mentioned criteria (reliability, cost, operational flexibility and impact on the environment) cannot be reasonably accounted for through a single scalar performance measure.

According to the multi-criteria optimization, in the selection of the number of capacitor banks, a pre-defined relative score is assigned to each of the four criteria within the knowledge base. As shown in Table 3.5, the assigned scores with respect to the reliability and operational flexibility criteria are

Table 3.5: Relative scores of reactive compensation alternatives, RS_k.

Number of Banks	Reliability	Cost	Environment	Operational Flexibility
10	10	1	1	10
9	9	2	2	9
8	8	3	3	8
7	7	4	4	7
6	6	5	5	6
5	5	6	6	5
4	4	7	10	4
3	3	8	9	3
2	2	9	8	2
1	1	10	7	1

proportional to the number of banks, while the scores related to the cost decrease as the number of banks increases (more banks → higher cost → worse evaluation of the alternative). Furthermore, the reliability scores are multiplied by a factor accounting for the fact that the reliability somewhat depends on voltage level (it is assumed that high-voltage level schemes are characterized by a higher reliability than those at lower voltages). The values of the relative scores shown in Table 3.5 are determined from experience.

For example, the first row of Table 3.5 states that with 10 capacitor banks the highest reliability and operational flexibility are achieved (scores of 10/10) while cost and impact on the environment have the worst measure (1/10). At the other extreme, with 1 capacitor bank, the lowest reliability and operational flexibility are obtained (weights of 1/10) while cost attains its best performance (10/10). Note however that the best bank arrangement in terms of impact on the environment (10/10) is achieved with 4 banks since this is a trade-off between the audible noise produced and the size of the bank (1 bank may be very large and require more space in the substation).

In addition, the above *fixed* relative scores placed on the different criteria should be multiplied by corresponding *user-preference* weights. Such weights represent the degree of relative importance that the designer wishes to assign to each of the four criteria. Thus, if the relative scores shown in Table 3.5 are defined by RS_{ik} where i = 1,..., 10 denote the design alternative and k = 1,..,4 represent the criteria while UPW_k, k=1,...,4 are the user preference weights, then the total evaluation score for each design alternative, TS_i, is defined by,

$$TS_i = \frac{1}{100} \sum_{k=1}^{4} RS_{ik} \quad UPW_k \tag{3.10a}$$

For example, one utility may stress cost over the other criteria and choose the vector UPW=[70,20,10,0] implying that 70% of the preference weight is assigned to cost, 20% to reliability and 10% to the impact on the environment with zero importance attached to operational flexibility.

Therefore, the procedure for selecting the number and rating of capacitor banks consists of: (i) identifying possible alternatives corresponding to the given voltage level, (ii) performing multi-criteria analysis on these alternatives and select the alternative characterized by the highest total score. The number and the rating of capacitor banks as well as the reactive capability of a single can are thus determined.

(c) The number and the characteristics of units. Having determined the number of banks and their rating, it remains to define their subcomponents, i.e. units. Each bank consists of a number of chains of units where a unit possesse the smallest reactive capability determined at the previous step. The minimum number of units per chain is at least 10 in order to avoid overvoltages higher than 10%. The total number of units per phase is however dependent on the reactive capability of a single unit (Qunit) and the reactive compensation required per phase (Qph). Thus, the following relations (3.10b) are used to define the remaining quantities (number of units per phase, number of chains and the voltage per unit):

$$\begin{aligned} N_{units} &= integer(Q_{ph} \ / \ Q_{unit}) \\ N_{chains} &= integer(N_{units} \ / \ 10) \\ V_{unit} &= E \ / \ (\sqrt{(3)} \ * \ N_{units}) \end{aligned} \qquad (3.10b)$$

The number of chains (Nchains) is based on 10 units per chain but a larger number is also acceptable. *Static VAR Compensators.* The specification of a complete Static Var compensator regardless of its type (TCR, TSC or combined) consists of the following items [Sta86]:

• General characteristics of the SVC such as nominal voltage, reference voltage, slope of the U-I characteristics, nominal reactive power rating, overloading capability, response time, harmonics, single-line diagram and layout and audible noise levels.

• Characteristics of system subcomponents such as the coupling transformer, capacitor banks, reactors, thyristor valves and control system equipment.

• Protection requirements for SVC subcomponents (transformer, main bus, capacitor banks, reactors and thyristor valves).

The general SVC characteristics are usually specified as a part of system studies. Therefore, it remains for the knowledge-based system to provide specifications for the system subcomponents. This activity is carried out through the low-level knowledge processing (equipment selection) and is discussed in more detail in section 3.8.

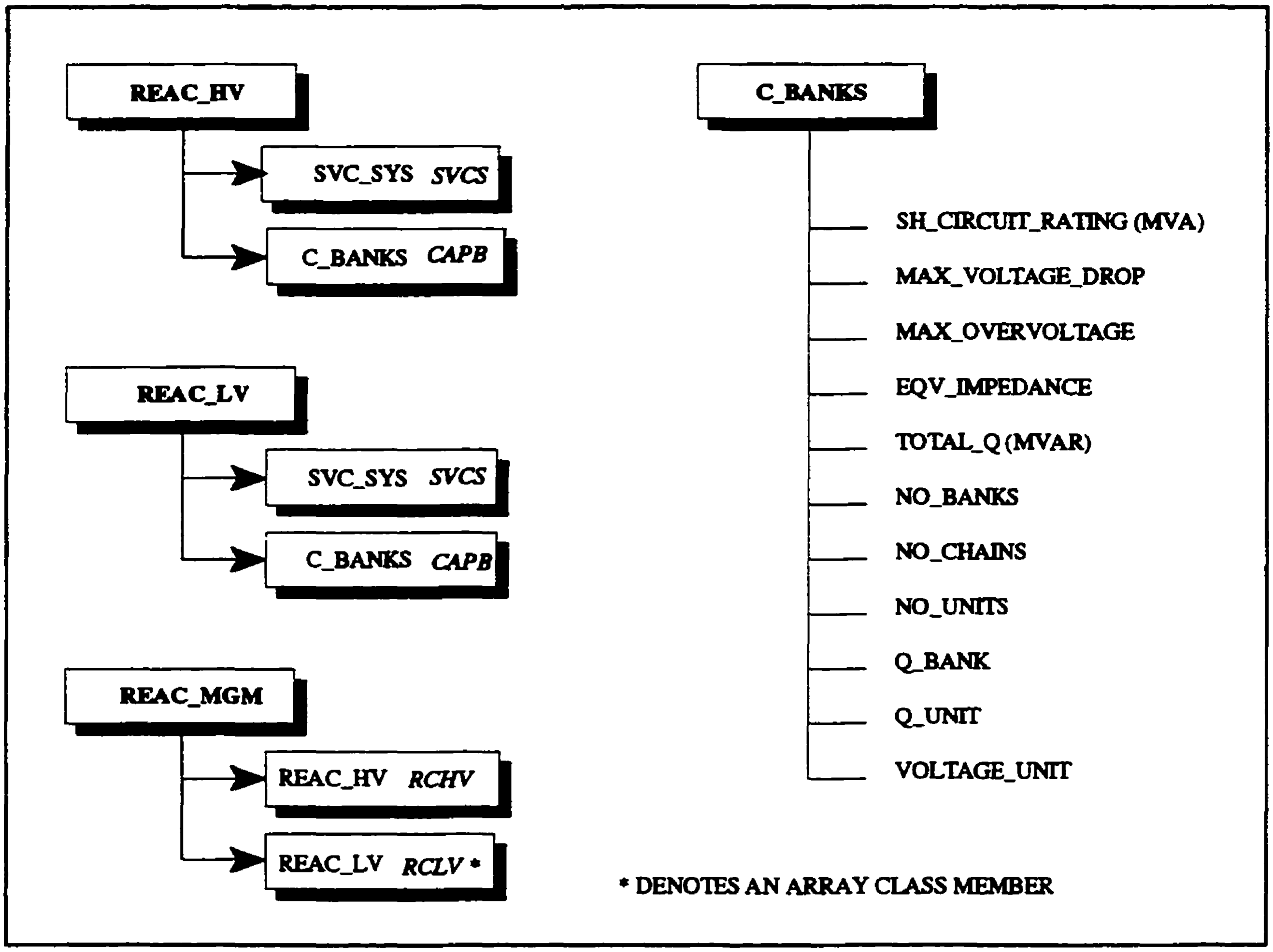

Figure 3.20: Reactive power management class model.

The object-oriented representation of the above-described reactive power management knowledge consists of the class structure depicted in Figure 3.20. Thus, the class "C_Banks" models all important parameters of the compensation system realized by shunt capacitor banks (total reactive power capability, number of banks, number of chains, number of units, bank and unit reactive capacities, voltage per unit, etc.). The class "SVC_Sys" contains members modelling the above-mentioned general characteristics of SVC. Both classes ("C_Banks" and "SVC_Sys") are, as shown in Figure 3.9, members of the classes "Reac_HV" and "Reac_LV" which encompass reactive power knowledge implemented at the high and low-voltage levels of a substation. Consequently, classes "Reac_HV" and "Reac_LV" contain two methods each, namely, *DefineCapBanks* and *DefineSVCsys* which encapsulate the above-presented knowledge for instantiating capacitor banks and SVC characteristics. Finally, the class "Reac_Mgm", a member of the main class "Simulation", encapsulates the entire information regarding reactive power considerations in a substation through its members "Reac_HV" and "Reac_LV" (instantiated for each substation low-voltage level).

It is important to mention that all the information provided through the instantiation of classes shown in Figure 3.20 is principally used when selecting the corresponding electrical equipment, in this case the reactive power compensation equipment. Thus, the instance of the class "Reac_Mgm" is passed to the constructor class of the shunt capacitors, shunt reactors or different types of SVC classes in order to enable their instantiation.

3.6.5 Reliability Evaluation of Design Alternatives

Reliability evaluation of design alternatives is accomplished using two main indices, namely, LOLP (Loss of Load Probability) and LOLE (Loss of Load Expectation)[End82]. The former is defined as a sum of probabilities of all failure states which can occur in the substation. The latter yields the value of the expected load shed due to failures and is determined as the sum of the products of the probability and the load shed associated with each failure state. The following formulae are used to calculate the above mentioned indices:

$$\begin{aligned} LOLP &= \sum p_i \\ LOLE &= \sum p_i * \Delta P_i \end{aligned} \tag{3.11a}$$

Where p_i is the probability of being in the failure state (state when the load shed occurs) and ΔP_i is the amount of load shed in state i.

There exist several approaches to the calculation of LOLP and LOLE for a given substation alternative. The most popular methods are based on the state-space Markov model [End82] and on the minimal-cut algorithms [End82]. The objective of both methods is to first determine the failure and normal operating states of the substation and to calculate their probabilities of occurrence. However, these approaches have not proven the most practical since substation single-line diagrams usually entail an extremely large number of possible Markov states and paths between source and load points which significantly complicates the task of identifying the failure states. Consequently, it can be concluded that a more efficient systematic method of identifying the failure and normal operating states of the substation will significantly improve the performance of the existing tools for the reliability analysis. The approach proposed here is based on the linear programming (LP) problem and is formulated as follows:

$$\begin{aligned} &\min \sum (d_k - y_k), \quad k \in d \\ &\begin{bmatrix} u \\ 0 \\ y \end{bmatrix} = A * S * x \\ &0 \le y \le d \\ &0 \le u \le u^{\max} \\ &0 \le x \le x^{\max} \end{aligned} \tag{3.11b}$$

where d is a vector of the given loads, u is the vector of input injections (incoming line flows), x denotes the vector of power flows inside the substation, y is a vector of output power flows, A is the incidence matrix of the station denoting its connectivity and S is a diagonal matrix containing the switching states of the station components (0 or 1) . For purposes of reliability, only the major components such as transformers, circuit breakers and busbars are considered. The objective function of the LP problem is to minimize the total amount of load shed for a given substation structure.

From the solution of the above-specified LP problem, it is possible to determine whether the state defined by a given matrix S is a failure state whenever the minimum load shed is different from zero. The next step is to calculate the probabilities of state occurrences which can be accomplished by solving the Markov state-space model [End82]. Obviously, if all possible Markov states are considered, the size of the problem increases astronomically. Therefore, in order to reduce the number of states examined, those states whose probability of occurrence is estimated to be very low are omitted. Another simplification which can be done consists of merging the states which have an equivalent impact on the overall system reliability, namely the same amount of load shed and the same probability. In spite of these measures of simplification, the size of the Markov model typically remains excessively large for easy handling. In order to overcome this obstacle, a new approach based on the concept of *reliability bounding* is proposed. This approach relies on the following assumptions:

• The development of the Markov state-space model for fully symmetrical single-line diagrams is relatively easy to accomplish. This is so since the number of states reduces significantly due to the numerous states which have the same impact on the reliability and thus can be merged into equivalent states.

•For every non-symmetrical single-line diagram, it is possible to find a symmetrical approximation whose reliability represents either a lower or an upper bound of the reliability of the original system. These bounds can be used as design parameters.

Thus, for a given substation single-line diagram, the first step is to identify a reduced set of states. The next step is to determine the most appropriate symmetrical single-line diagrams whose levels of reliability may accurately represent lower and upper reliability bounds to the given substation. Then, each of these states is analyzed through the LP program in order to find the failure states. The last step consists of finding the lower and upper bound reliability indices (LOLP and LOLE). The LOLP and LOLE values characterizing lower and upper reliability bounds depend on the number of incoming and outgoing circuits, on the selected number of transformer units as well as on the reliability characteristics of the main equipment components (failure and repair rates).

The class "Reliability" which is a part of the class "Simulations" preserves the complete information related to the reliability analysis. Thus, its properties are the main indices (LOLP and LOLE) as well as the parameters characterizing the Markov state-space model such as a set of failure and normal states and their corresponding probabilities of occurrence. In addition, the class "Reliability" contains methods which perform the LP problem and solve the Markov equations. Furthermore, this class contains the method which selects the most appropriate single-line schemes from the database whose reliability levels represent the upper and lower bounds of the reliability of the given substation.

3.6.6 Cost Evaluation

The total cost of a substation is defined in terms of three basic components: investment cost, cost of operation and cost of interruptions.

The investment cost of a substation comprises the cost of installed equipment, capital cost of terrain and transmission line rights-of-way and construction costs. These costs are generally expressed as life-cycle costs. Life-cycle costs reflect the present worth of all annual charges over the life of a substation. They are calculated by multiplying the initial capital investment by the so called life-cycle multiplier [US78]. This multiplier takes different values for depreciable property (whose value changes with time) and non-depreciable property (whose value does not change with time). Thus the total investment costs applicable for alternative comparison purposes can be calculated as follows:

$$DP = K_1 * D_1$$

$$ND = K_2 * D_2$$

$$CT = DP + ND$$

where DP denotes the total cost of depreciable property, ND is a total cost of non-depreciable property, D_1 and D_2 are initial costs of depreciable and non-depreciable properties respectively, K_1 and K_2 are corresponding life-cycle multipliers and CT is a total life-cycle investment cost [US78]. The cost of non-depreciable property does not specially affect the comparison of alternatives since these costs are the same for each alternative (costs of terrain and right-of-way), however the construction costs may take slightly different values for different alternatives.

The costs of operation include the cost of losses and of maintenance. The costs of losses include costs of power transformer losses, losses generated by shunt reactors and losses associated with SVC equipment. The cost of losses is calculated by multiplying the total losses by a fixed constant expressed in \$/MW. Maintenance costs depend on the substation single-line-diagram as well as on the type of equipment which is installed since different types of electrical apparatus require different efforts and time for maintenance. Given an approximate maintenance cost for each piece of electrical apparatus, the maintenance costs are estimated on the basis of the scheduled annual substation maintenance programs depending on the substation single-line-diagram and the expected maintenance due to component failures.

The cost of load interruptions is very difficult to estimate. It is based on the reliability indices such as the frequency and duration of the failure state associated with load curtailment as well as on the characteristics of the load itself since load curtailment may affect some customers more severely than others. The following equation can be used in order to assess the costs of load interruption [Bil87],

$$IC = \sum_{i} * f_i * \sum_{j} m_j \, c_j(d_j) \tag{3.12}$$

where IC denotes the total cost due to interruptions, f_i is the frequency of occurrence of event "i" expressed in number of occurrences per year while c_j (d_j) is the interruption cost in \$/kW for a duration of d_j hours to customer "j" and m_j is the load in kW not supliedto customer “j” for event “i”.

The interruption cost vs duration is established for different kinds of customers (residential, storage heating, electrical industry etc.) through statistical analysis [Bil87].

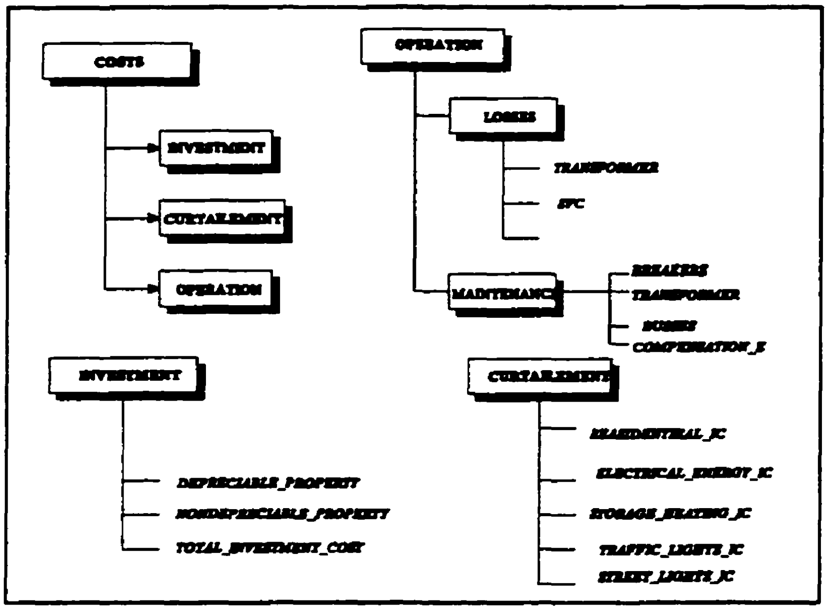

Figure 3.21: Cost analysis class model.

The total cost of a design alternative is finally calculated as the sum of all the above-mentioned cost components (investment cost and the capitalized cost of operation and interruptions).

A simple class model of substation cost considerations, presented in Figure 3.21, consists of three classes modelling three basic components of substation total cost. Thus, the classes "Investment", "Operation" and "Curtailment" are all members of the main class "Costs" which is, in turn, a member of the class "Simulation". These classes, as shown in Figure 3.21, contain properties corresponding to the above-described cost parameters. In addition, each class has methods containing the knowledge presented above which is implemented in order to calculate the total substation cost. The final product of the cost analysis simulation tool is therefore a class instance preserving the complete information about the costs of a particular design alternative.

3.6.7 Multi-objective Comparison of Design Alternatives

Once a set of feasible design alternatives has been established, the last important design step is to evaluate these alternatives and to select the preferred final design. There are several approaches to the evaluation process depending on the chosen criteria such as reliability, cost or operational flexibility. Another important aspect to be considered is the impact of a design on the environment. The most common methods of design evaluation and comparison are based either on the calculation of various reliability indices as described in the previous section or on the total cost of the installation. In addition, reliability and cost analysis can be combined through the calculation of the so-called cost of interruption which accounts for the cost of power-not-supplied to different types of customers [Bil87]. As for the evaluation of operational flexibility or impact on the environment, these are more difficult to quantify but still possible by using indices which can serve for comparison of alternatives.

While a comparison can be performed relatively easily with respect to reliability or cost alone, this task becomes more difficult when taking into account four criteria namely, cost, reliability, operational flexibility and impact on the environment. Since these criteria are fairly distinct, a common index or objective function which analytically encompasses the influence of each criteria would be difficult if not impossible to define. However, there exist various methods in *multi-objective analysis* as discussed in Section 1.5 which can be used to solve this comparison problem. Thus, the weighted-sum multi-objective strategy [Mas88] can be implemented in substation design according to the following steps.

Step 1. Determine the equivalent percentage scores of each design alternative with respect to the four basic criteria (cost, reliability, operational flexibility and impact on the environment). Two kinds of activities are performed here. First is the conversion of the reliability and cost indices to an equivalent percentage score and, secondly, the calculation of percentage scores with respect to operational flexibility and the impact on the environment. The former activity is carried out as follows.

Compare the values of relevant evaluation indices (LOLP or LOLE, Cost) among the various design alternatives and adopt the maximum (minimum) value as the best performance (100 % score). Find, then the percentage scores corresponding to other design alternatives. For example, the cost of the least expensive design alternative will be taken as a 100% score while the cost of all other more expensive alternatives will be assigned a smaller percentage score proportionally to the cost difference with respect to the 100% value.

This type of conversion to a percentage score can also be carried out for reliability since reliability can also be quantified by using the straight-forward explicit procedures shown in sections 3.6.5. In this procedure, the percentage values are converted into the relative scores (1-10).

In contrast to cost and reliability, the two remaining criteria (operational flexibility and impact on the environment) cannot be as easily quantified, however their relative scores can be determined on an approximate basis. Therefore, when operational flexibility is considered, the total score is obtained according to the following formulae:

$$SCORE_{OP} = \alpha * \left(\sum SLD\right) / nl + \beta * \left(\sum EQP\right) / neq + \gamma * \left(\sum PROT\right) / nl \tag{3.13}$$

where $SCORE_{OP}$ denotes the total score characterizing the given design alternative with respect to the operational flexibility criterion. The variable SLD is a relative score assigned to the substation busbar arrangements, EQP is a relative score characterizing the substation switching and compensation equipment, while PROT is a score assigned to the various implemented protection systems. Each of these three quantities is assigned a relative score from 1 to 10 with regard to operational flexibility according to the nature of the subsystem it represents. In addition, nl is the number of voltage levels in the substation, neq is the number of different types of circuit breakers, while α, β and γ are weighting factors accounting for the importance given to the substation single-line-diagram, switching equipment and protection flexibility respectively. Thus, the equivalent score characterizing operational flexibility of a substation alternative is obtained as an averaged combination of the scores of these three basic design ingredients. The values of α, β and γ are usually set to 0.5, 0.2 and 0.3 respectively thus assigning the greatest importance (0.5) to the choice of the selected single-line-diagram on the overall design flexibility. As for the type of substation switching equipment, its choice mostly affects the operational flexibility through different maintenance and operational capabilities of circuit breakers, while the properly selected protection scheme may significantly improve the system operational capability. The operational flexibility of the reactive power compensation system is evaluated according to its capability to supply the required amount of reactive power in order to maintain the desired voltage profile (e.g. SVC is characterized by a much higher score than the system consisting of capacitor banks in terms of operational flexibility).

Similarly, the following expression can be used to calculate the equivalent score when impact on the environment is considered as a criterion:

$$SCORE_{ENV} = \rho * (\sum EQ_{SW}) / nsw + \sigma * (\sum EQ_{TR}) / ntr \qquad (3.14)$$

where $SCORE_{ENV}$ is the equivalent score of a design alternative with respect to the impact on the environment criterion. Here, EQ_{SW} is the relative score from 1 to 10 assigned to different types of breakers (nsw), EQ_{TR} is a score characterizing various types of transformer units (ntr) while ρ=0.3 and σ=0.7 are the weighting factors representing the relative importance assigned to switching equipment and transformers with regard to their impact on the environment. In this case, tranformers are believed to have a stronger impact (0.7) on the environment than switching equipment (0.3).

Step 2. Having determined equivalent scores for each of the four basic criteria, the overall evaluation of the design alternative is found using the following expression:

$$SCORE_{TOT} = W_{REL} * SCORE_{REL} + W_{COST} * SCORE_{COST} + W_{OP} * SCORE_{OP} + W_{ENV} * SCORE_{ENV} \quad (3.15)$$

where W_{REL} , W_{COST} , W_{OP} and W_{ENV} are user preference weights given as part of the input specification and $SCORE_{TOT}$ is the overall evaluation value of a design alternative.

The class structure shown in Figure 3.22 models the knowledge related to the multi-objective

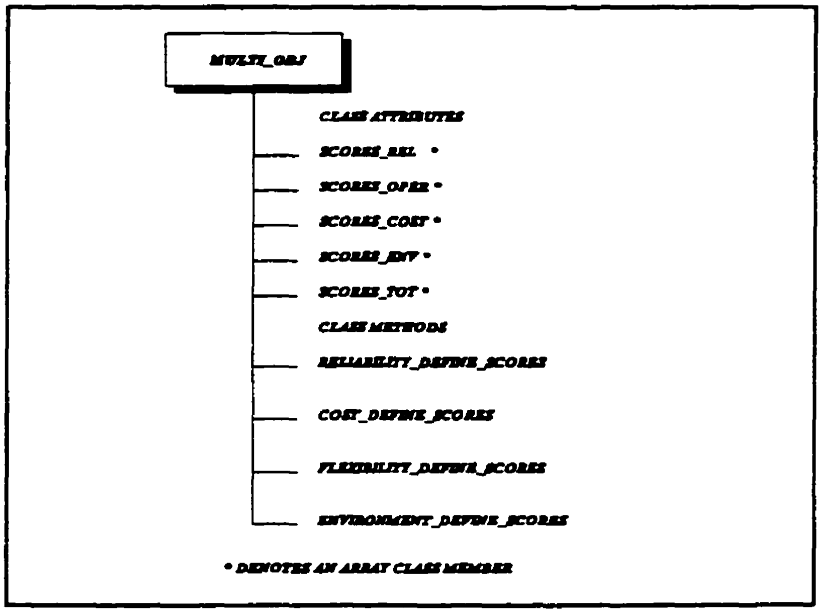

Figure 3.22: Multi-objective analysis class model.

analysis. The attributes of the main class "Multi-Obj" are total scores of each design alternative with respect to the four considered criteria. The above-described simulation knowledge is encapsulated in class methods which are called upon to calculate the values of the above-mentioned scores.

An example of multi-criteria evaluation of design alternatives is given in Chapter 4 as part of the complete example of the substation design session carried out by SIDE.

3.6.8 Mechanical Stress Analysis in Substations

The large mechanical forces which occur as a consequence of short-circuit faults may seriously affect parallel electric conductors whose length is large compared to the distance between them. The mechanical stresses which result are particularly critical when rigid busbar conductors are considered. This requires the calculation of anticipated stresses on the busbar conductors including those stresses which affect the busbar supports. The following expressions are used to accomplish these necessary calculations [ABB88]:

$$
\begin{aligned}
F_H &= 0.2*I^2*l/a \\
F_T &= 0.2*(I/t)^2*l/a \\
\sigma_H &= V_\sigma*\beta*F_H*l/(8*W) \\
\sigma_T &= V_\sigma T*F_T*l_T/(8*W) \\
F_S &= V_F*\alpha*F_H \\
\sigma_{res} &= \sigma_H+\sigma_T
\end{aligned}
\tag{3.16}
$$

where F_H and F_T are electromagnetic forces which exert stress on the main conductors and conductor elements, σ_H and σ_T are the corresponding mechanical stresses, F_S is the stress on the support points, I is the value of the peak short-circuit current, l is a distance between supports, "a" denotes distance between conductors belonging to the same phase, V_σ and V_F are vibration factors (both equal to 1 for AC installations), W is a conductor section modulus, α and β are support stress and main conductor stress factors and σ_{res} is a resultant stress on the conductor.The conductors are considered to be short-circuit proof [ABB88, West52] when the following conditions are satisfied:

$$
\begin{aligned}
\sigma_{res} &\leq 1.5*R_p \\
\sigma_{Ts} &\leq R_p
\end{aligned}
\tag{3.17}
$$

If the above conditions are not met, the distance between supports, the type of conductor or the number of conductors per phase or the distance between them should be readjusted. The values for readjustments are recommended by experience-based heuristic rules contained in the method which performs mechanical stress analysis and which is a member of the class "Mech_Stresses". This class in turn contains properties modelling all the above-mentioned mechanical stress parameters. The class "Mech_Stresses" is a member of the family of simulation procedures and as such belongs to the class "Simulations".

3.7 Substation Design Methodology

3.7.1 Substation Design Process

The substation design process is a collection of activities organized so as to lead to one or more acceptable designs. The important characteristic of the substation design process is that independent distributed knowledge can be processed at predetermined design steps [Ata95-2].

Thus, given the input design specification, the first step in the design process is to perform simulations such as preliminary analysis of transformer units, short-circuit analysis, insulation coordination and reactive power management.

The next step is to identify all viable arrangements for high-voltage and low-voltage buses, transformer/compensation groups and high and low-voltage line terminations as well as to combine these arrangements into feasible single-line diagrams. An attempt has been made here to emulate the human expert's way of reasoning by providing a set of starting single-line configurations for each of the composite groups and by eliminating those which cannot satisfy the imposed design constraints.

Once the simulations have been completed and the single-line diagram constructed, the selection of substation electrical equipment for each single-line-diagram alternative is carried out. Electrical characteristics such as current-carrying capacity, insulation and short-circuit withstand capabilities as well as the ability to cope with environmental conditions (ambient temperature, pollution, altitude) are all taken into account.

The last step in the design process is to evaluate all the generated design alternatives in terms of cost, reliability, operational flexibility and impact on the environment.

The substation design activities associated with the above-mentioned design steps are carried out by a constructor of the class "Designs" which is depicted in Figure 3.23. The instance of this class embodies the complete design session, i.e., the input specifications, the information related to each generated design alternative (single-line-diagram, electrical equipment, evaluations) as well as data concerning simulations, all of which are preserved inside the class. Thus, as shown in Figure 3.23, the class members are instances of the classes "Input", "Simulation", "Arrangements", "Alternatives" and "Substation". An instance of class "Input" stores the complete input design specification, an instance of class "Simulation" preserves all results generated by the simulation tools, while instances of classes "Arrangements" and "Alternatives" encompass all considered feasible single-line configurations for each of the five substation composite parts and the complete single-line-diagram alternatives. The class "Substation" is an aggregate class member which models the entire design including detailed descriptions of the substation's single-line configuration and electrical equipment specifications. Since several design alternatives are considered and compared during the design session, the class member "Substation" is specified to be of the aggregate type allowing the storage of a number of its instances.

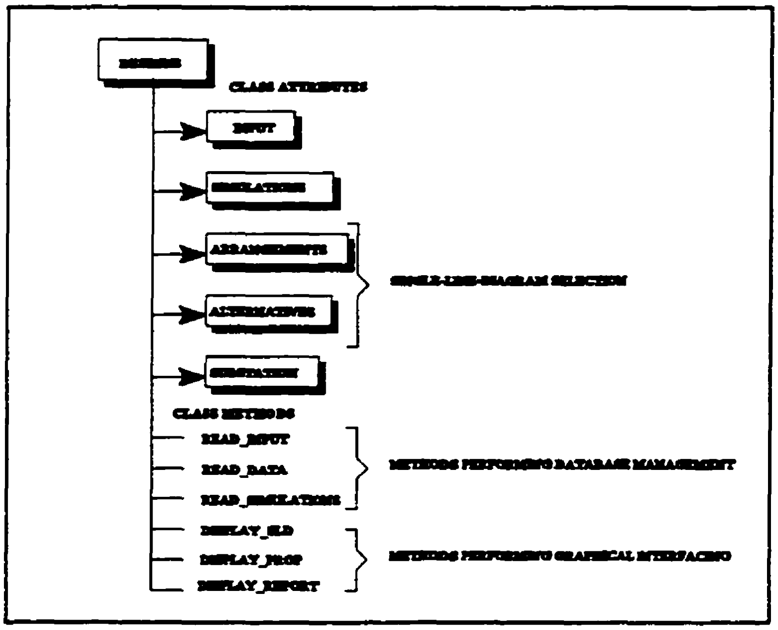

Figure 3.23: Class model of the entire design session.

Apart from the *class attributes* described above, the class "Designs" contains a set of *class methods* to carry out database management and interfacing activities. Hence, the methods "ReadSimulations", "ReadSubstationData" and "ReadInput" provide access to the simulation results, to the generated design alternatives (instances of class "Substation") and to the existing input specifications respectively. Furthermore, the methods "DisplaySLD", "DisplayReport" and "DisplayProperties" permit the display of the substation single-line-diagram, allow access to the design report and enable displaying the properties of the selected electrical apparatus. Additionally, it is important to mention the method "VerifyInput" which contains the feasibility constraints on the design specifications. The knowledge rules contained in this method check the entered input specification data and, if some of the data are not feasible (e.g. unrealistic values for temporary or slow-front overvoltages or short-circuit levels, non-standard voltage levels etc.), it issues appropriate warnings (adjustment suggestions) and interrupts the program execution.

Class constructors are considered as special methods whose role is to perform class instantiations. The class constructor of the "Design" class invokes, in sequence, the constructors of the classes "Input", "VerifyInput", "Simulation", "Arrangements", "Alternatives" and "Substation", thus performing the substation design activities. The one exception is the method "VerifyInput" which is not a constructor, but is invoked after the "Input" object has been created in order to verify the validity and feasibility of the design specifications. The concept of knowledge sub-division into *Top-level* and *Low-level* (Chapter 1) is applied here such that the activities associated with the construction of the substation single-line-diagram are categorized as *top-level* knowledge, while the knowledge related to the selection of substation electrical equipment is considered as *low-level* knowledge.

The following sections describe in more detail the knowledge associated with the substation design activities as well as the knowledge processing at each of the above-mentioned design steps.

3.7.2 Simulation Procedures

The necessary simulations related to the substation design process have been described in detail in Section 3.6. They are usually performed during two stages of the design, at the beginning, in order to calculate the design parameters used in the other design stages and at the end, when the evaluation of the design alternatives is performed. The order of their execution is now discussed.

The preliminary analysis of transformer units is conducted first to determine the number, the ratings, the impedance and the tap changing requirements of the power transformers. These data are then used together with the input specifications (voltage levels, network short-circuit capacity, etc.) to determine short-circuit stresses which can occur in the substation.

The reactive power analysis is carried out next to determine the amount of reactive power compensation, the means by which this compensation is to be accomplished (capacitor banks, SVCs) as well as the pertinent characteristics of these compensation devices (number of banks, number and rating of capacitor units per phase and reactive capacity of the bank).

The last simulation which has to be accomplished at the first design stage is insulation coordination which provides values of standard withstand voltage levels and safety clearances used when selecting the substation electrical equipment.

The set of simulations run at the second stage of the design consists of the cost and reliability analysis and the multi-criteria evaluation of the generated design alternatives.

3.7.3 Selection of the Substation Single-Line Diagram

The construction of the substation single-line diagram (SLD) is one of the most important design activities carried out in order to determine the electrical equipment and how it is to be connected. The knowledge processing at this stage involves global decision making regarding the fundamental configuration of the substation. Consequently, the domain knowledge associated with the SLD selection has been classified as *top-level* (Chapter 4) knowledge.

The construction of the substation SLD consists of two steps: (i) to select from the available arrangements feasible configurations for each substation constituent group (buses, line terminations, transformer groups) and (ii) to combine these groups into complete feasible single-line-diagrams which meet the specified design criteria and constraints. The object-oriented model of the domain knowledge related to the SLD selection embodies two classes, both members of the previously described main class "Designs". These are the class "Arrangements" which encapsulates the knowledge associated with the first step (selection of feasible arrangements for each constituent part) and the class "Alternatives" which contains the knowledge connected with the second activity

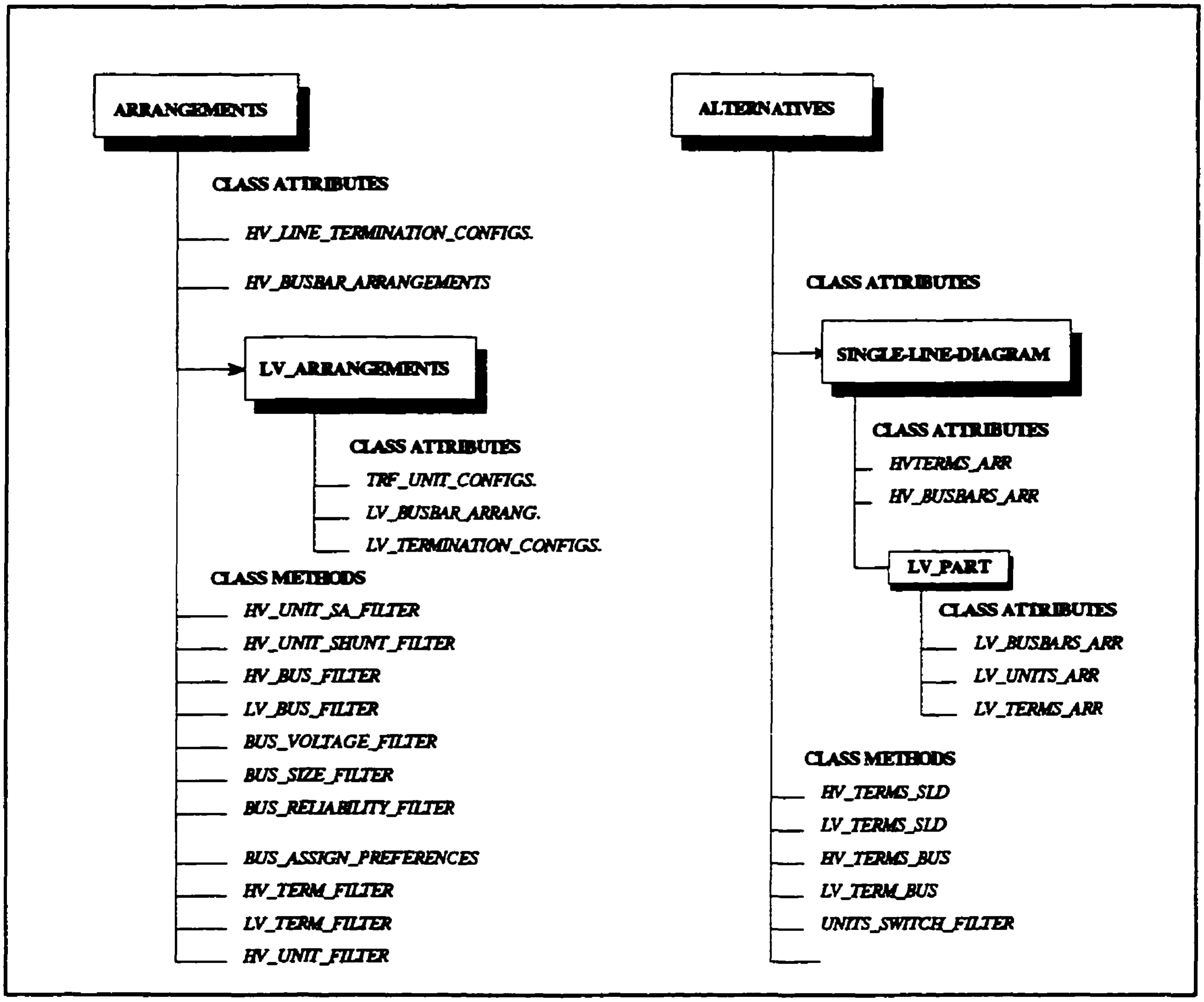

Figure 3.24: Single-line-diagram selection - the class model.

(construction of the complete SLD from previously selected feasible parts).

Figure 3.24 depicts the structures of these two classes outlining the properties and methods which embody the SLD knowledge rules. Thus, the methods of the class "Arrangement" analyze the available configurations of busbars, line terminations and transformer groups and filter out those which do not satisfy the given design specifications. The methods of the class "Alternatives" consider all selected five-part configurations, put them together and, according to their embedded rules, eliminate those configurations which do not meet the specified design criteria. The attributes of the class "Arrangements" are arrays containing feasible arrangements for each of the five substation composite groups. For example, the attribute "HV_Busbar_Arrangement" contains possible busbar arrangements all of which satisfy the specified design criteria. On the other hand, since there may be several low-voltage levels in the substation, the attributes referring to low-voltage buses, line terminations and transformer groups are all structured as attributes of the class "LV_Arrangements" which belongs to the main class "Arrangements" and is instantiated for each low-voltage level.

The class "Alternatives" which is also shown in Figure 3.24, contains a set of complete single-line-diagram alternatives constructed from previously found feasible five-part arrangements (stored as attributes of the class "Arrangements"). The main attribute of the class "Alternatives" is thus the class "Single_Line_Diagram" which models the substation single-line-diagram. As expected, the attributes of this class correspond to the substation's five constituent groups. Similarly, as in the case of the class "Arrangements", the existence of several low-voltage levels in the substation is accounted for by modelling the low-voltage part of the substation by a separate class, "LV_Part" containing low-voltage buses, transformer groups and low-voltage line terminations as its attributes. This class is accordingly instantiated several times, that is, one for each low-voltage level in the substation.

The design activities associated with the two above-mentioned steps for defining the SLD of a substation are now discussed in more detail in terms of the selection of feasible arrangements for each of the substation composite groups.

3.7.3.1 Selection of Substation Busbar Arrangements.

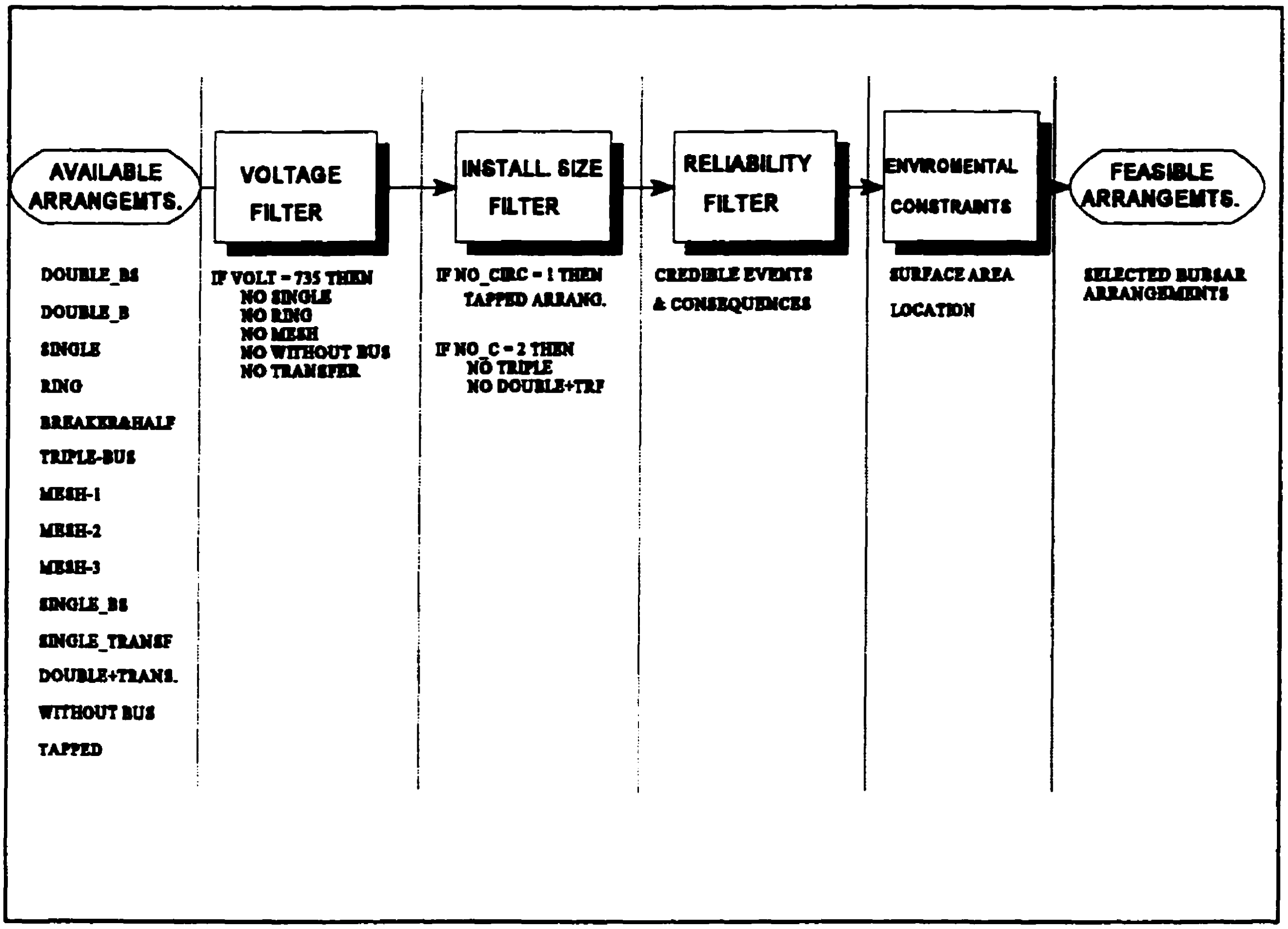

Figure 3.25: Selection of substation busbar arrangements.

The selection of substation busbar arrangements (for each voltage level in the substation) is the most critical activity in the single-line-diagram construction process. This is so not only because of the importance of the substation buses in terms of the overall reliability and operational flexibility of the substation but also because their choice influences the selection of the arrangements of other substation composite groups. Thus, the busbar arrangement selection is usually the first step when defining the substation single-line-diagram.

As already noted, an attempt has been made here to emulate the human expert's way of reasoning, that is, given a set of starting busbar arrangements, the human expert eliminates those which cannot satisfy the imposed design constraints and narrows down the search to a set of plausible choices. In a similar way, SIDE applies a set of filters which contain heuristic rules to eliminate all infeasible arrangements. This filtering process is outlined in Figure 3.25 and discussed as follows.

The set of all considered busbar arrangements is passed as an input to the first filtering module. This module contains knowledge rules which filter out the received arrangements with respect to the given voltage levels in the substation retaining only those which are feasible. For example, if a high-voltage such as 765 kV is to be implemented in the substation, the appropriate rule will eliminate ring-bus, single-bus and single-bus-with-transfer-bus arrangements, all of which are not recommended for such a high voltage. On the other hand, the rules will retain a variety of double-busbar arrangements and breaker-and-a-half configurations for further consideration.

The next filter considers the installation size (number of circuits, number of transformer units) and further filters the remaining set of busbar arrangements. Thus, for relatively large substations (more than four circuits) arrangements such as tapped or mesh are not recommended and are consequently removed from the list of potential candidates.

The reliability filter is considered the most important one since it ensures that the reliability criteria are met. Given the specified set of credible events to consider (EV) as well as the set of consequences to avoid (CS), the reliability filter evaluates each busbar arrangement from the remaining set of potential candidates. Thus, each busbar arrangement is analyzed off-line in terms of the consequences which appear when subjected to a list of considered credible events (Section 3.5) and the results of this analysis are stored in the database. Therefore, when evaluating an arrangement, the reliability filter uses these off-line results to determine if the considered busbar arrangement ensures that the undesired consequences *do not* occur when the specified credible events are applied. For example,

Table 3.6: The off-line reliability evaluation of single-busbars-without-sectionalizers.

CS/ EV	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8	CS9	CS10
EV1			✔							
EV2	✔									
EV3	✔									
EV4	✔									
EV5	✔									
EV6	✔									
EV7	N.A.									

when single-busbars with sectionalizing breakers are considered, the credible event "breaker-fault" leads to the disconnection of two parallel lines in the substation. This fact is established off-line and, if the consequence of this event (in this case "two parallel lines out") is unacceptable as part of the reliability input criteria, the filter will discard single-buses with sectionalizing breakers as a non-feasible arrangement. Table 3.6 presents an example of the off-line analysis preformed in order to evaluate one busbar arrangement (single-buses-without-sectionalizing-breakers). The checkmarks denote the most severe consequence which appears when the considered credible event (EV1-EV8) occur. The following nomenclature is used in Table 3.6:

- EV1 - One circuit-breaker out of service followed by a line fault (CBOOS + LF)
- EV2 - Line fault plus breaker failed to trip (LF + BFT).
- EV3 - Breaker out of service plus line fault with breaker failed to trip (CBOOS+LF+BFT).
- EV4 - One breaker out of service plus breaker fault (CBOOS+BF).
- EV5 - One bus out of service plus breaker fault (BUSOS+BF).

- EV6 - One bus out of service plus line fault (BUS)S+LF).
- EV7 - Two buses faulted simultaneously (2BUSF).

The considered potential consequences (CS1 - CS10) resulting from aforementioned credible events are listed in order of decreasing severity as follows:

- CS1 - Complete substation outage (All Lines)
- CS2 - Two parallel lines out + one series line out (2PARL+1SERL)
- CS3 - Two parallel lines out (2PARL)
- CS4 - Two series lines out + tie-line out (2SERL+TIEL)
- CS5 - Two series lines out + station split (2SERL+ST_SPLIT)
- CS6 - Two series lines out (2SERL)
- CS7 - One line + tie-line out (1LINE+TIEL)
- CS8 - One line out + station split (1LINE_+STSPLIT)
- CS9 - One line out (1LINE)
- CS10 - Station split (ST_SPLIT)

The last filter in Figure 3.25 takes care of the environmental constraints. Thus, the reduced set of busbar configurations remaining is first checked against environmental conditions such as size of installation. This test ensures that the surface area of the terrain will be large enough to accommodate certain types of busbar arrangements. For example, given the approximate dimensions of the busbar electrical apparatus as well as the rough dimensions of the available terrain and the number of incoming/outgoing circuits one can estimate whether the installation with the considered buses can fit into the available space. In addition, the location of the substation (indoor, outdoor) and the configuration of the terrain may not be suitable for certain kinds of arrangements thus influencing the filtering process at this stage.

Table 3.7: Busbar arrangements relative scores.

Criteria / Arrangement	**Cost**	**Reliability**	**Operational Flexibility**	**Impact on the Environment**
Double-buses-with-sectionalizers	1	10	9	2
Double-buses-without-sectionalizers	6	8	8	7
Ring buses	4	5	6	3
Breaker-and-half-arrangement	2	9	10	9
Single-buses-with-sectionalizers	9	3	3	9
Single-buses	8	1	1	9

Once a set of the feasible busbar arrangements has been determined, it remains to rank them according to the user preference weights vis-a-vis the four main criteria. Multi-criteria analysis (discussed in Section 1.5) is again employed in order to facilitate this task. Table 3.7 outlines the relative scores assigned off-line to the various kinds of busbar arrangements with respect to the four criteria. The determination of these scores is based on experience and, unlike the user preference weights, is not a user input.

In order to calculate the total evaluation score for a given busbar arrangement, the relative scores provided in Table 3.7 are multiplied by user preferences weights (a part of design specifications) for each of the above-four criteria and then summed up. All feasible alternatives are then ranked according to this total evaluation score.

The above-described filtering and ranking activities are all performed by class methods from the class "Arrangements". Thus, the main method "HV(LV)BusFilter" first invokes methods which perform filtering ("HV(LV)BusVoltageFilter", HV(LV)BusSizeFilter", "HV(LV)BusReliabilityFilter" and "HV(LV)BusEnvFilter") in the order shown in Figure 3.25. Having chosen the feasible busbar configuration, the main method calls upon the method "BusAssignPreferences" in order to evaluate and rank these feasible busbar arrangements. The main method eventually returns the list of recommended busbar arrangements ranked in descending order of their overall performance with respect to the four fundamental criteria (reliability, operational flexibility, cost and impact on the environment).

3.7.3.2 Selection of Substation Line Terminations.

The selection process of high-voltage and low-voltage line termination arrangements is relatively simple since it mostly depends on the given input specifications. In other words, the specifications should contain most of the important data describing the desired configuration of line terminations such as the type of conductor (overhead conductors, cables), the communication facilities (wave traps), compensation equipment (shunt reactors) and any special metering equipment (additional instrument transformers).

Thus, given the input specifications, the method "HVTerminationsFilter" (or "LVTerminationsFilter" when the low-voltage level of the substation is considered) which belongs to the class "Arrangement" (Figure 3.24) considers first the voltage level and filters out some of the arrangements from the database (Figure 3.3) which are not applicable. For example, for voltage levels above 345 kV, the configurations having underground cable conductors are eliminated from consideration.

The switching facilities are then analyzed depending on the busbar arrangement which was selected in the previous step. Hence, if the chosen busbar arrangement possesses enough current-interrupting capacity (e.g. double-busbars which are always equipped with two or at least one breaker per incoming/outgoing circuit connection) the line circuit breaker can be omitted and the line termination can have only a disconnector to enable switching off of the line for maintenance purposes.

As for the above-mentioned characteristics related to the communication, compensation and metering facilities as well as the type of the conductor, they are all specified as part of the design specifications. The method "HV(LV)TerminationsFilter" then looks into the database and selects, from among those arrangements which satisfy the previously analyzed voltage and switching conditions, the one which contains the specified electrical equipment.

3.7.3.3 Selection of Substation Transformer/Compensation Groups.

The Transformer/Compensation groups comprise the biggest number of possible configurations. As previously discussed, the insulation, the switching requirements, the protection, the station supply as well as the reactive power compensation requirements strongly influence the TC groups configuration. The rules processed at this stage (in the class "Arrangements") identify the arrangements satisfying insulation, station supply and reactive compensation requirements. This is accomplished as follows.

The transformer/compensation group configurations are first classified into three major categories according to the insulation protective equipment (surge arresters) they possess, namely, (i) those having arresters at both transformer terminals, (ii) with one surge arrester at the high voltage transformer side and (iii) without surge arresters. Each of these categories is then further subdivided according to the station supply, grounding and compensation equipment they may have. Therefore, it is possible to distinguish six sub-groups of arrangements, namely, (i) those having a station supply auxiliary transformer connected as a shunt element to the main circuit, (ii) the station supply connected at the main transformer's tertiary winding, (iii) the arrangements having a grounding transformer providing the path for zero-sequence currents when the "delta" winding connection is implemented in the main transformer, (iv) the reactive compensation realized by an SVC at the main transformer's tertiary winding, (v) the same as (iv) with shunt capacitor banks and (vi) an arrangement having neither of the above mentioned equipment.

Given the design specifications, the selection process identifies first one of the above-mentioned three main categories, that is, depending on the location of the substation (indoor, outdoor) as well as on the voltage levels (Range 1 or Range 2 [IEC71]), the rules embedded in the method 'HV_Unit_SA_Filter" determine how many surge arresters are needed. For example, if the high-voltage part of the substation is located outdoors, the presence of the surge arrester is compulsory in order to protect the internal insulation against lightning strokes. Furthermore, if the voltage level belongs to the Range 2 (above 245 kV) surge arresters are needed to ensure protection against switching overvoltages.

Having selected the main category, the next step is to consider the compensation, service supply and grounding requirements in order to choose one of the six sub-categories. The specification factors which are taken into account here are the transformer connection (if a delta secondary, a grounding transformer may be required), the availability of the tertiary winding (station supply or Var compensation may be connected to a tertiary), as well as the compensation requirements (SVC or capacitor banks must be connected). The rules contained in the method "HV_Unit_Shunt_Filter" are processed in order to determine the appropriate set of transformer/compensation arrangements.

Both above-mentioned methods ("HV_Unit_SA_Filter" and "HV_Unit_Shunt_Filter") are invoked in sequence inside the main method "HV_Unit_Filter" which returns several selected feasible transformer group configurations. The final selection of one arrangement depends on the switching and current-interrupting requirements and is carried out during the construction of the complete single-line-diagram as discussed in the following paragraph.

Once the feasible configurations for each of the five composite groups have been selected, it remains to put them together in order to obtain the complete single-line-diagram of the substation. The fact that there may be several possible arrangements for each of the composite parts implies that the number of their combinations representing the full SLD of a substation can be significantly large. However, not all combinations are feasible, i.e. a set of restrictions is imposed to filter out those SLD's which are not realizable or are not recommended since they introduce undesired redundancies.

3.8 Electrical Equipment

The substation electrical equipment is classified according to the following categories (Figure 2.2, Chapter 2):

- Switching equipment (breakers and disconnectors)
- Transformers (power, instrument, grounding)
- Electrical conductors (overhead lines, cables and busbars)
- Protection equipment (surge arresters, protective relays)
- Compensation equipment (shunt reactors, shunt & series capacitors, static compensators)

The class hierarchy presented in Figure 2.2 (Chapter 2) which constitutes the object-oriented model of the electrical equipment was developed according to the above sub-division. In this Chapter, more detailed descriptions of the main electrical apparatus implemented in substations is provided. This description encompasses not only the physical characteristics of electrical apparatus but also the knowledge which is processed in order to select the appropriate equipment to satisfy the given design specifications.

First, the common characteristics of the above-mentioned equipment categories are discussed. The most important representatives of each equipment category such as circuit breakers from the switching equipment group, power and instrument transformers from the transformer group, electrical busbars from the conductor group, surge arresters from the protection group and compensation equipment in general are elaborated in greater detail.

3.8.1 Switching Equipment

Switching equipment in electric power systems incorporates basically two groups of devices, namely, circuit breakers and disconnectors. As shown in Figure 2.2 (Chapter 2) these groups are further subdivided into various types of circuit breakers and disconnectors. Thus, it is possible to distinguish among extra-high-voltage circuit breakers, circuit breakers for shunt capacitor banks, standard disconnectors, load disconnectors and grounding switches. All switching apparatus share a number of common properties such as maximum voltage for the equipment, nominal current rating, insulation withstand voltage levels and short-circuit withstand capability. Figure 3.26 presents the object-oriented class model of switching equipment with the class "Switching_Equip" containing common properties inherited by the subclasses "Cr-Breaker" and "Disconnector". The latter two model

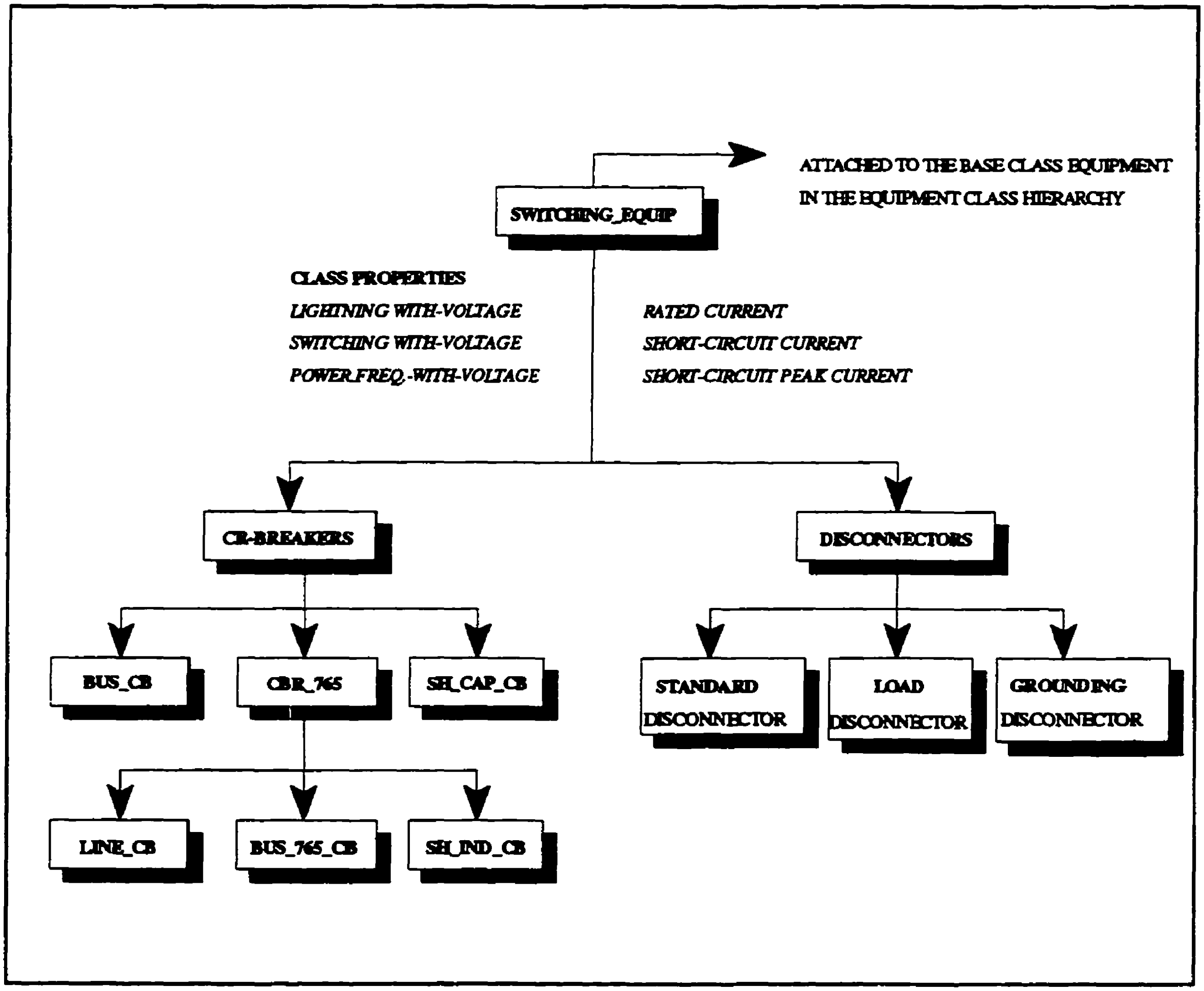

Figure 3.26: The switching equipment class model.

families of circuit breakers and disconnectors respectively.

The role of standard disconectors in power networks is to divide or sectionalize different parts of the network either to isolate the faulty circuits where a fault was previously interrupted by cicuit breakers or to separate certain parts of the network for maintenance purposes. In contrast to standard disconnectors, load disconnectors possess the capability to interrupt the rated load current. The third kind of disconnectors, the so-called grounding switches, serve to provide a ground connection in order to improve safety during maintenance. Disconnectors, in general, are not very sophisticated components and, accordingly, they do not possess numerous properties. Thus, apart from the properties inherited from the parent class "Switching_Equipment", the class "Load_Disconnector" contains properties characterizing the disconnector's interrupting and closing capabilities. Similarly, the class "Grounding_switch" has a property which symbolizes the capability of the grounding switch to close under short-circuit conditions. It is important to mention that disconnectors (particularly standard disconnectors), although they can appear as independent components, are often considered as being part of a circuit- breaker block since their operation is frequently in conjunction with the operation of circuit breakers. The selection of disconnectors is performed by a constructor of one of the three subclasses (load, standard or grounding) upon request placed by either the constituent part class to whom the disconnector belongs or by the circuit breaker constructor if the disconnector is part of the breaker. The selection process consists mostly of verifying whether electric properties such as rated current and voltage, short-circuit capability and insulation strength of a particular disconnector object in the database satisfy the specified design criteria.

As for the circuit breakers, they represent a fairly complex switching apparatus whose role is to switch off and on electric circuits under normal and faulty conditions. Such switching often involves an arc extinguishing process which makes the circuit-breaker task more complicated and its structure, accordingly, more complex. Therefore, since circuit breakers represent one of the most important power system components, the following paragraphs describe in greater detail the classification of circuit breakers, their structure, their selection process as well as the corresponding object-oriented model.

The circuit breaker selection process consists of three main steps, namely, to select the circuit-breaker type, to verify the specified design criteria and to check for derated conditions if applicable. These stages are now discussed in detail.

The subdivision of circuit-breaker types has been made according to their interrupting medium (SF6, air-blast, oil, vacuum) and according to their construction characteristics (live tank, dead tank). Thus, seven circuit-breaker types are distinguished by SIDE: *SF6 dead tank, SF6 live tank, air-blast dead tank, air-blast live tank, minimum oil, bulk oil* and *vacuum*. Given the input design specification, the first step in the selection process is to recognize types which satisfy the voltage level and substation site location constraints. This task is accomplished through rules which are constructed to ensure that the proper circuit-breaker types will be selected for the given voltage levels and location. For example, it is well known that vacuum circuit-breakers cannot be implemented at voltages higher than 35 kV. Similarly, only SF6 and air-blast breakers are recommended for extra-high voltages. As for the site location, the rules filter out types depending on whether a circuit- breaker is to be located indoor or outdoor. One example is the restriction imposed on bulk-oil circuit-breakers which states that these are not recommended for indoor installations since they can cause severe damage and a fire in a case of oil spill. Thus, an example of a typical rule processed at this step is as follows:

IF (25 kV ≤ *voltage* ≤ 245 kV) && (*location* = "indoors")
THEN *breaker_types* = "SF6_dead_tank, min_oil, air_blast_dead_tank"

The second step in the selection process is to choose the preferred type among the feasible ones selected in the previous step. This is realised using multi-criteria analysis of the feasible circuit-breaker types with respect to the four considered criteria, namely, reliability, cost, operational flexibility and the impact on the environment. As is the case with other multi-criteria tasks performed by SIDE, the method of weighting sums is also used here (Section 1.5). The fixed relative scores of each circuit-breaker type are summarized in Table 3.8.

The combined total evaluation score which enables comparison of the overall design alternatives is obtained as the sum of the multiples of the above relative scores for each alternative design and the corresponding user preference weights. The alternatives are then ranked according to the scalar value of this total score.

Table 3.8: Circuit-breaker types relative scores.

Criteria / Breaker Type	Reliability	Operational Flexibility	Cost	Impact on Environment
SF6	10	9	4	7
Air-blast	4	7	2	10
Minimum oil	6	6	2	4
Bulk oil	6	2	10	1

Once the selection of a circuit-breaker type has been accomplished, it remains to verify the circuit breaker's electric properties. These properties are: the nominal current rating, the interrupting capacity, the insulation withstand capability (lightning, switching and power frequency) and the interrupting time. This verification task is carried out as follows.

The database with circuit breakers is scrolled and a subset containing circuit breakers matching the previously selected type (SF6, Air-blast, minimum oil or Bulk oil) is extracted. The circuit breakers from this subset are then examined one by one by the following rule:

IF (*breaker_current_rating* > operating_current) &&

(*breaker_lightning_w_volt* > lightning_overvoltage) &&

(*breaker_switching_w_volt* > switching_overvoltage) &&

(*breaker_power_freq_w_volt* > temporary_overvoltage) &&

(*breaker_interrupt_capacity* > short_circuit_current) &&

(*breaker_interrupt_time* < required_fault_interr_time)

THEN

Select *circuit-breaker*

The italicized quantities on the left hand side denote circuit-breaker properties while the quantities on the right hand side in the conditional part of the rule indicate the corresponding system parameters.

The last step in the circuit-breaker selection process is to verify that the prescribed normal service conditions and the operating duty are satisfied. These conditions include the ambient temperature range (-50, 40 °C) and the altitude above sea level (less than 1000 m) while the operating duty incorporates the standard breaker duty cycle (CO-15-CO)[1]. If these conditions are not met, the following corrections must be made:

- correction of nominal current rating due to higher or lower ambient temperature,
- correction of voltage stress due to the higher altitude above sea level,
- correction of interrupting and closing capabilities due to a non-standard duty cycle.

The correction of the nominal current rating due to an increase in the ambient temperature is accomplished through the calculation of the *continuous load current capacity based on actual ambient temperature*. The latter quantity is determined from the following empirical expression [AnsiC37]:

$$I_a = I_r * [(\theta_{\max} - \theta_a) / \theta_r]^i \qquad (3.18)$$
$$i = 1 / 1.18$$

where I_a is the allowable continuous load current in amperes at the actual ambient temperature (it cannot exceed two times I_r), I_r denotes the rated continuous current in amperes, θ_{max} is the allowable

1

Breaker duty cycle defines the sequence of breaker switching operation. For example, the standard cycle cycle CO-15-CO [AnsiC37] means that the breaker performs an closing-opening action, stays open for 15 sec and then repeats the closing-opening action.

hottest spot total temperature, θ_a is the actual ambient temperature expected (-30, 60 C) and θ_r is the allowable hottest spot temperature rise at rated current in degrees Celsius. The values for θ_{max} and θ_r are determined based on the type of circuit breaker selected and on the maximum voltage for the equipment specified. These values are summarized for various circuit-breaker types in [AnsiC37]. For example, for an SF6 circuit breaker with a rated voltage greater than 72.5 kV, the values for θ_{max} and θ_r are 65 and 105 C° respectively.

Two correction factors should be calculated in the case of equipment installation at an altitude higher than 1000 m. The following formulae are used in order to compute these factors [AnsiC37]:

$$\begin{aligned}
&IF\ alt > 1500 \\
&K_{cr} = (0.99 - (0.99 - 0.96) * (alt - 1500) / (1500)) \\
&K_{vol} = (0.95 - (0.95 - 0.8) * (alt - 1500) / (1500)) \\
&IF\ alt < 1500 \\
&K_{cr} = (1 - (1 - 0.99) * (alt - 1000) / (500)) \\
&K_{vol} = (1 - (1 - 0.95) * (alt - 1000) / (500))
\end{aligned} \tag{3.19}$$

where K_{cr} and K_{vol} are the correction factors that multiply the equipment rated current and maximum voltage respectively in order to obtain the upgraded values valid at the actual altitude (alt).

Finally, when a non-standard duty cycle is required, the circuit breaker rated interrupting and closing capabilities must be modified. This is accomplished by means of the reclosing capability factor R (%) which is determined as follows [AnsiC37],

$$\begin{aligned}
R &= 100 - D \\
D &= d_1 * (n - 2) + d_1 * (15 - t_1)/15 + d_1 * (15 - t_2)/15 + \ldots
\end{aligned} \tag{3.20}$$

where D represents the total reduction factor (%), d_1 denotes a factor which accounts for the circuit breaker symmetrical interrupting capacity at operating voltage, n is the total number of openings required and t_1, t_2 ... is a sequence of reclosing time intervals less then 15s. The upgraded values for the short-circuit current and the related required capabilities (interruption capability , closing capability) are then obtained by multiplying the corresponding rated quantities by the calculated reclosing capability factor R.

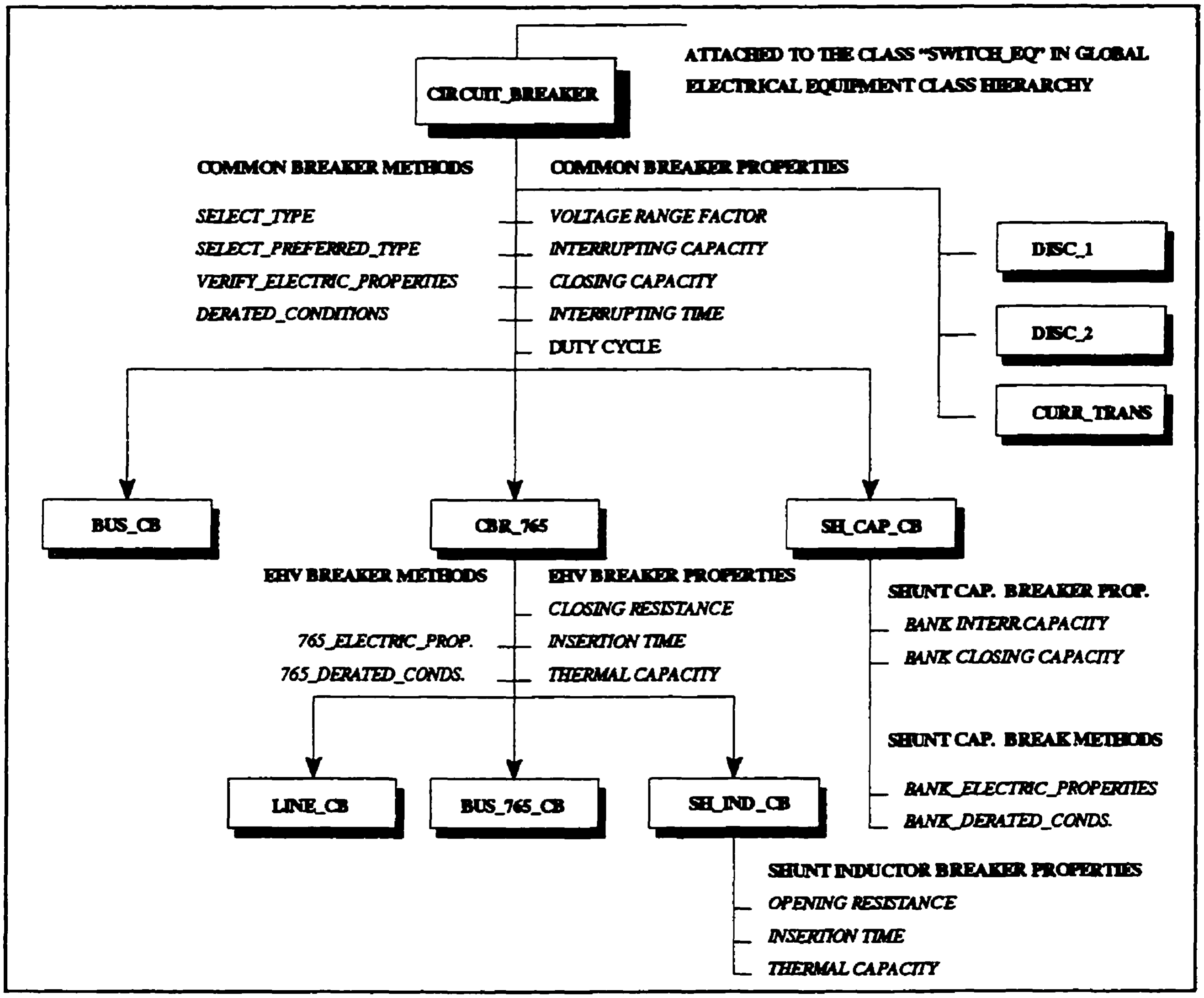

Figure 3.27: The circuit-breaker object-oriented class hierarchy.

The basic characteristics of the domain knowledge related to the circuit-breaker selection process have been discussed in previous paragraphs. A more elaborate object-oriented model of circuit-breakers as used in SIDE is now described.

There exist several categories of power circuit breakers depending on their mode of application. These are extra-high voltage circuit breakers, those used at voltages below 500 kV and shunt capacitor circuit breakers. They all share a large number of common characteristics, such as maximum operating voltage, rated current-carrying capacity, interrupting and closing capability, etc. An important characteristic of all circuit breakers is that they possess compound properties, i.e. properties which are instances of other classes. Firstly, one or two disconnectors (Disc_1 and Disc_2 in Figure 3.27 both instances of the class "Disconnector") are usually associated with a circuit breaker in order to enable the isolation of circuits after circuit breaker operation. Secondly, one current transformer (instance of the class "Curr_Trans") is always implemented (for protection purposes) either as a physical part of the circuit breaker (dead tank) or as a separate component (live tank). Apart from these common attributes, circuit breakers from each category possess their own specific properties. For example, shunt capacitor circuit breakers have special properties related to the interruption and closing capability of circuits containing shunt capacitor banks, while extra-high voltage circuit breakers have closing/opening resistors as a particular construction characteristic. Furthermore, the extra high-voltage circuit breakers are subdivided into three sub-categories, namely, line_breakers, bus_and_transformer breakers and shunt_reactor breakers.

Figure 3.27 presents the object-oriented hierarchical structure of power circuit breakers corresponding to the above categorization. The mechanism of inheritance is extensively used here due to the existence of a large number of common properties. Moreover, the methods encapsulating the above-presented knowledge for circuit breaker selection ("Select_Type", "Select_Preferred_Type", Verify_Electric_Properties", Derated_Conditions") are also inherited since the selection stages are the same for all types of circuit breakers requiring the same main task to be carried out (type selection, verification of electric properties, derated conditions). However, since some of the selection rules are slightly different for diverse breaker categories, the mechanism of polymorphism is successfully implemented here. One example of this is in the method "DeratedConditions", in the case of shunt capacitor breakers, where the interrupting and closing capabilities of shunt capacitor circuits (due to non-standard duty cycles) have to be modified in addition to the standard interruption capability corrections. Thus, the common part of the method is inherited from the top class "Circuit_breaker" (method "Derated_Conditions" in Figure 3.27) while the specific part ("BankDeratedConditions") is defined in the class "Sh_cap_cb".

Note that the object-oriented circuit breaker class hierarchy presented in Figure 3.27 is a part of the global electrical equipment class hierarchy shown in Figure 2.2 from Chapter 2. The circuit-breaker class hierarchy is attached to the class "Switch_Eq" (Figure 2.2) from which it inherits properties common, not only to circuit breakers, but also to other electrical equipment. These properties are, for example, insulation levels (switching, lightning and power frequency), maximum operating voltage and cost.

The instantiation of a particular circuit breaker in the substation is accomplished through the action of a class constructor of the corresponding circuit breaker subclass shown in Figure 3.27. This action is triggered by methods of the class modelling a constituent part of the substation to which the circuit breaker belongs. The first step in the instantiation process is to create the circuit breaker sub-components namely pertinent disconnectors and current transformer. The second step is to invoke methods which will perform circuit-breaker type selection and verification of electric properties and derated conditions. This process is accomplished as follows. The methods for the type selection ("Select_Breaker_Type" and "Select_Preferred_Type") are invoked first to determine the desired circuit-breaker type. The electrical equipment database is then searched and a set of circuit breakers matching the specified type is extracted. The circuit breaker with the lowest current rating among them which satisfies the design criteria (checked by method "Verify_Electric_Properties") is selected. If standard operating conditions are not satisfied the method "Derated_Conditions" is called upon to perform the necessary adjustments of current and voltage characteristics.

3.8.2 Transformers

The main role of transformers in power networks is to transfer electrical energy from systems of one voltage level to systems of another voltage level. Another purpose of transformers can be to transform current/voltage such as to enable the connection of protective and metering devices which are usually designed to operate with much lower values of voltage and current then those of the network. Consequently, electrical transformers can be classified in two basic categories: power transformers and instrument transformers. Further subdivision brings the current and potential transformers as sub-classes of the instrument transformer class. Figure 3.28 displays the transformer

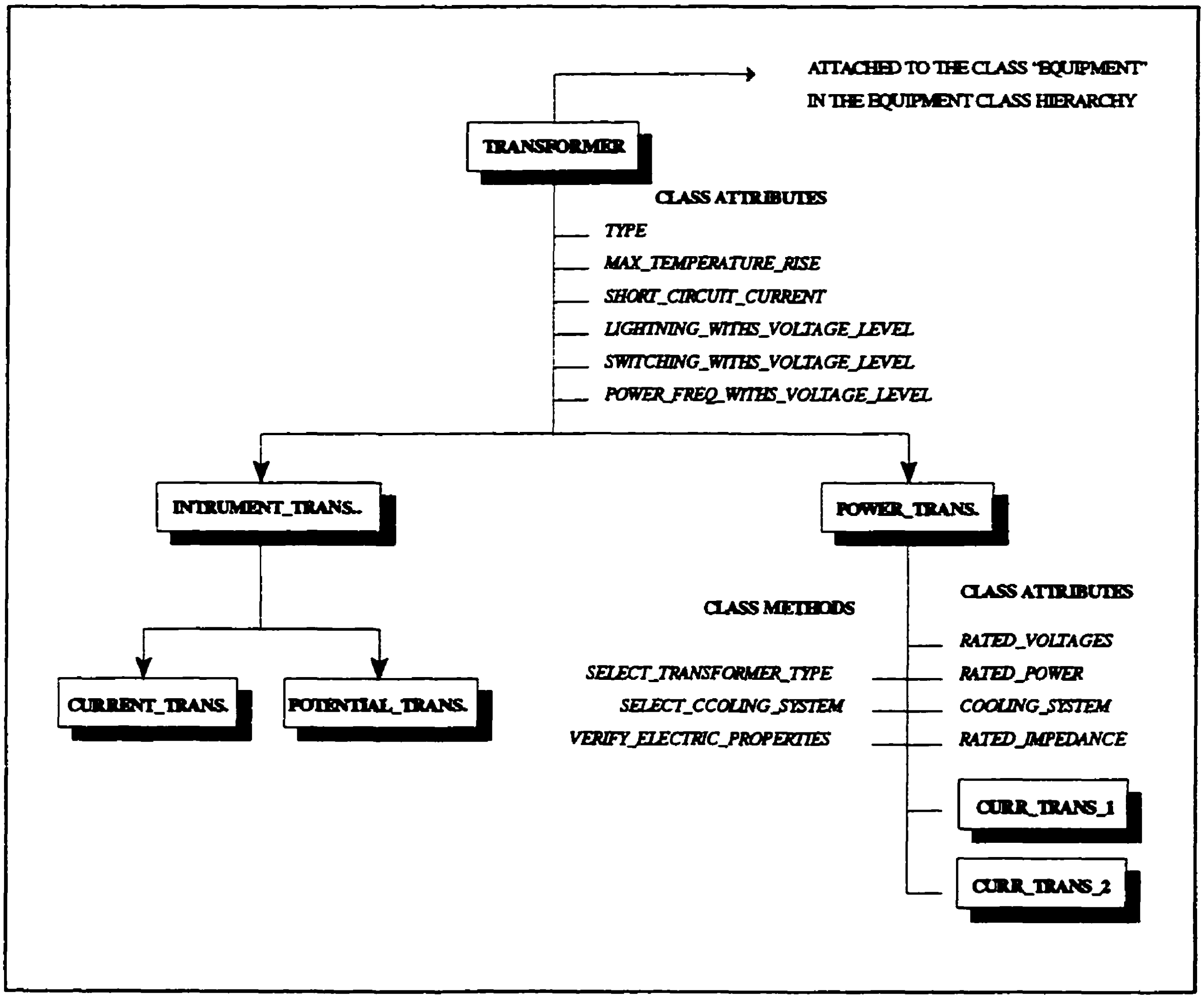

Figure 3.28: The "Transformer" class hierarchy.

object-oriented class model whose components are discussed in more detail in the sections below.

The purpose of current transformers [ABB88, CAN] is to transform the primary current within prescribed error limits in order to enable the connection of low-current protective and metering devices. In contrast to the power transformers which are connected in parallel, current transformers are always connected in series with an electric circuit. The current transformer selection process consists of two steps: to select the transformer type and to verify if electric properties satisfy the design criteria. These steps are now discussed as follows.

Table 3.9: The current transformer type selection.

Type of CT	Voltage	Location	Application
WOUND-DRY	≤ 25 kV	INDOOR	DT, PT
SINGLET-DRY	≤ 25 kV	INDOOR	LT, LB
SINGLET-CAST-RS	25 - 38 kV	INDOOR	LT, LB
SINGLET-MIN-OIL	≤ 735 kV	OUTDOOR	LB, LT
WOUND-MIN-OIL	≤ 735 kV	OUTDOOR	DT, PT, SH

DT - Dead tank circuit-breaker
LT - Live tank circuit breaker
LB - Line/Bus
PT - Power transformer
SH - Shunt reactor

Depending on the winding construction characteristics, current transformers can be divided in two groups, namely, *wound-type* and *single-turn* transformers. The former are usually implemented as bushing transformers, tank transformers or miniature transformers. The latter are used as outdoor straight-through, bar or slipover transformers [ABB88]. According to the insulation medium, four different categories are distinguished: dry, cast -resin, oil-impregnated and paper/porcelain. Thus, when both insulating medium and construction characteristics are considered, several equivalent transformer types are obtained. Which type will be selected depends on various factors such as system voltage level, location (indoor, outdoor) and intended application (if it is to be installed in a line/bus conductor, as a part of a dead-tank circuit breaker or as a part of the power transformer). Table 3.9 presents the equivalent current-transformer types considered by SIDE and summarizes the basic knowledge used for the type selection.

One example of a rule which is derived from Table 3.9 and is used for the type selection purposes is as follows,

IF (*System_voltage* $\leq$ 735 kV) &&
(*Location* = OUTDOORS) &&
(*Application* = PT)
THEN
(*CT_Type* = WOUND-MIN-OIL)

In addition to the common properties which they share with other members of the transformer family (insulation levels, rated primary current and voltage, short-circuit capacity), current transformers have their own particularities, among which one can mention accuracy class, number of cores and rated burden of each core as the most representative ones. These parameters are usually provided from protection studies.

The rule which filters the current transformer database also checks the insulation levels, the nominal operating characteristics and the short-circuit capabilities and eventually selects the object whose accuracy class and burden meets the values obtained from protection studies.

The object-oriented model of current transformers consists of the "Current_Trans" class, presented in Figure 3.28 as a member of the overall family of electric transformers. Apart from the inherited properties, this class also possesses two methods, namely, "SelectCT_Type" and "Verify_Electric_Properties" which are called upon by the constructor of the "Current_Trans" class in order to instantiate the current transformer. As mentioned above, current transformers are mostly implemented in conjunction with other major equipment such as circuit breakers, power transformers and shunt inductors. Thus, their instantiation is usually requested by the class constructors of these major equipment classes. Rarely can current transformers be employed independently. For example, if some special metering is required in branches which are not equipped with the above-mentioned major equipment. The "Current_Trans" class constructor acts independently upon request from the relevant constituent part class (which models the branch) to which this current transformer belongs.

The role of potential transformers (Pt) in power networks is analogous to that of current transformers. Hence, Pt's are employed to measure voltage or to provide connections for protective relays but, in contrast to Ct's, they are connected in parallel with network circuits.

Table 3.10: Potential transformer type selection rules and relative scores.

Pt Type	Voltage	Location	Cost	Reliability	Flexibility	Environment
IN-2-RES	≤ 25 kV	INDOOR	-	-	-	-
IN-1-MO	≤ 25 kV	OUTDOOR	10	9	9	6
IN-2-MO	≤ 25 kV	OUTDOOR	8	7	5	7
IN-1-O	25 - 735 kV	OUTDOOR	-	-	-	-
CAPAC	≥ 315 kV	OUTDOOR	-	-	-	-

IN-2-RES - Inductive, two-phase insulation, resin
IN-1-MO - Inductive, single-phase insulation, minimum oil
IN-2-MO - Inductive, two-phase insulation, minimum oil
IN-1-O - Inductive, single-phase, oil
CAPAC - Capacitive

There exists several types of Pt's depending on the insulating medium, the type of winding connection and the principle of operation. Thus, when the operating principle is considered, there are two types of Pt's: *inductive transformers* whose construction is based on the classical transformer theory and *capacitive transformers* which operate on the capacitive divider principle. Inductive Pt's are typically manufactured in two forms, namely, Pt's with two-phase insulation and Pt's with single-phase insulation. As for the insulating medium, resin and oil are usually employed. Similarly, as in the case of current transformers, several factors influence the decision of which Pt type to select. Apart from the system voltage level and the transformer location, the four fundamental design criteria (cost, reliability, operational flexibility and impact on the environment) must be considered when choosing the preferred type when inductive Pt's are considered. As for the capacitive Pt's, they are usually preferred for extra high voltage systems. Table 3.10 outlines the basic knowledge which is processed when determining the Pt's preferred type, including the multi-criteria relative scores with respect to the four basic criteria. Note that relative scores are not provided for capacitive, single-phase inductive and two-phase resin potential transformers since these types are exclusively used in specific situations and do not have any alternative.

An example of a rule derived from Table 3.9 is given by:

IF (*System_voltage* ≤ 25 kV) &&
        (*Location* = OUTDOOR) &&
THEN
        IF (*IN-1-MO_scores* ≥ IN-2-MO_scores)
        THEN
                (*Type* = IN-1-MO)
        ELSE
                (*Type* = IN-2-MO
        END
END

Similarly to current transformers, the accuracy class and rated burden are also typical characteristics of Pt's except that the accuracy class is calculated based on the voltage error as opposed to the Ct's where the class is related to the current error. These and other common properties such as insulation and short-circuit levels are all inherited through the parent class "Instrument" (Figure 3.28).

In contrast to current transformers, potential transformers are implemented independently, that is, they are not tied to any major electrical apparatus. They are usually employed in line terminations to measure voltage at the entrance of the substation or in transformer sections. Thus, their instantiation is triggered by class constructors modelling line termination or transformer section composite groups which invoke the constructor of the class "Potential_trans". The instantiation process is accomplished in the same manner as in the case of current transformers through the methods "SelectPTType" and "VerifyElectricProperties.

As in the case of circuit breakers, the selection of power transformers is carried out in several steps, namely, the selection of the *transformer type*, the selection of the *cooling system* and the verification of *electric properties* such as insulation strength, short-circuit and loading conditions. These steps are summarized in the following subsections.

There are three items which constitute the type of transformer unit: *the insulating medium*, the construction characteristics of the magnetic core and the type of winding connection. According to the insulating medium, transformers can be divided into the following categories: *dry-type*, where core and windings are not contained in an insulating liquid, *oil-immersed*, where oil (with a fire point less than 300 °C) represents the insulation medium and the coolant, and *silicon* where a synthetic liquid (mostly silicon) having a fire point greater than 300 °C is used as the insulating medium. As for the construction characteristics of the magnetic core, there are two possibilities: the transformer can be realized as one *three-phase unit* or composed of three *single-phase units*. When the winding connection is considered, transformers are grouped as *auto transformers* the windings of which are connected in line and *two-winding transformers* where the windings are in parallel and galvanically separated. Thus, OIL-SINGLE-AUTO denotes an oil-immersed auto-transformer assembled from three single-phase units.

Therefore, the knowledge associated with transformer selection can be divided into three main groups: the knowledge processed to determine the type of insulating medium, the knowledge related to the choice of the construction and the knowledge associated with the selection of the winding connection. As far as the insulating medium is concerned, the voltage level, the location and the power rating of the transformer are constraints which are first considered. The following rule takes care of these constraints:

IF (*system_voltage* ≤ 28.4 kV) **AND**
(*location* = indoor) **AND**
(*unit_rating* ≤ 5 MVA)

THEN
(*transformer_insulation* = {DRY, OIL, SILICON})

ELSE
(*transformer_insulation* = OIL)

Table 3.11: The insulating media relative scores.

Criteria / Ins.medium	Environment	Cost	Reliability
DRY	10	7	3
OIL	1	2	8
SILICON	4	3	5

Thus, as implied by the rule, all three types of insulation are possible when the substation is located

Table 3.12: The construction type relative scores.

Criteria / Construction.	Cost	Reliability	Environment	Operational flexibility
3 single-phase	3	7	8	8
1 three-phase	9	5	4	6

indoors and the voltage level and power rating are less than the specified values. In that case, multi-criteria analysis is implemented in order to decide which of the three insulating media is preferred. Table 3.11 summarizes the relative scores of these media with respect to the three criteria (reliability, cost and impact on the environment). The final choice of insulating medium is chosen based on the user weighted sum of these scores.

Multi-criteria analysis is further applied to determine whether three single-phase units are to be used or one three-phase unit is the preferred option. Table 3.12 contains the relative scores of these two options with respect to the four criteria.

Thus, as can be concluded from Table 3.12, the 3 single-phase assembly is more reliable, more flexible but, also, a more costly alternative. Which option will be preferred depends also on the user preferred criteria which is accounted for through the user preference weights.

The last stage in the transformer type selection consists of determining the transformer winding connection. This is accomplished by first processing the following rule of thumb:

IF ($turn\_ratio \le 3$) **AND**

($winding\_arrangement \in$ {Yy, Ynyn, Yny, Yyn})

THEN

(*winding_connection* = {2-win, AUTO})

ELSE

(*winding_connection* = 2-win)

Table 3.13: Relative scores for winding connection arrangements.

Criteria / W. Arrangement	Cost	Reliability	Environment	Operational Flexibility
AUTO	10	4	6	8
2-WIN	6	7	6	6

Table 3.14: The cooling system relative scores.

Criteria / Cooling system	Cost	Reliability	Environment	Operational Flexibility
ONAN	10	7	5	2
ONAF	6	3	4	6
OFAF	3	1	3	7
ONAN/ONAF/ONAF	6	6	4	8
ONAN/ONAF/OFAF	3	5	3	10
ONAN/OFAF/OFAF	1	6	4	8

Hence, when the turns ratio takes on a value less than 3 and the winding arrangement belongs to one of the types described in the rule, both winding connections are possible and multi-criteria analysis must be used once again to choose one over the other. If, on the other hand, one of the rule conditions is not satisfied, the two-winding connection is chosen. Table 3.13 presents the multi-criteria relative scores for the two alternatives, two-winding (2-win) and auto transformers (AUTO).

Once the type selection has been accomplished, the next step in the transformer selection process is to choose the transformer cooling system. The method of cooling is usually stated by the manufacturer in the form of four capital letters where the first two letters denote the coolant and the manner of circulation for the winding while the last two letters indicate the coolant and the manner of circulation for cooling outside the transformer. Thus, the letter "O" denotes a liquid coolant with a fire point less than 300 °C (usually oil), "A" stands for air coolant, "N" indicates cooling by natural circulation and "F" symbolizes cooling by forced circulation [ABB88, AnsiC57]. For example, "ONAF" denotes a cooling system where natural circulation of oil is used for windings and forced circulation of air is implemented to cool the outside of the transformer. Obviously, air is exclusively used as a coolant for the outside of the transformer. As for the windings, the coolant is always oil for oil-insulated transformers while air is used in the case of dry (air-insulated) transformers. The choice of the manner of circulation depends on the designer preferences and is therefore accomplished by means of multi-criteria analysis. Table 3.14 contains the relative scores of the various cooling alternatives considered.

The last step in the transformer selection process is to verify whether the transformer's electrical characteristics satisfy the specified design criteria. These characteristics are the insulation levels, the power ratings and the short-circuit levels. Similarly to the case of circuit breakers, those transformers of a selected type and cooling system are extracted from the database and analysed by rules which filter out those which fail to satisfy the specified design criteria. For example, as far as the power rating is concerned, the approximate power rating obtained from the preliminary transformer analysis is used as a threshold when finding a set of transformers which match the transformer type and the cooling system. The subset thus obtained is further reduced by eliminating those units whose insulation and short-circuit levels do not meet the prescribed criteria. Eventually, the transformer with the smallest rating (first above the threshold) is selected from the feasible set.

The object-oriented model of power transformer consists of the class hierarchy outlined in Figure 3.28. The main class "Power_Transformer" inherits common properties such as insulation and short-circuit levels from the class "Transformer" which in turn models transformers in general (power and instrument). It also contains its own particular properties such as rated power, voltage levels and impedance and two class members ("Curr_Trans_1" and "Curr_Trans_2" both instances of the class "Current_Trans") modelling current transformers physically located at both sides of the power transformer and used for differential protection (the class "Current_Trans" will be described later in this chapter).

Since power transformers are part of the transformer section composite group, the transformer selection process is triggered by methods of the class "Units" which models this composite group as a part of the instantiation process of the group's pertinent electrical equipment. The power transformer instantiation process starts by sending a message to the class constructor of the "Power _Trans" class. Two instances of the "System_Input" class are then passed containing data related to the two voltage levels of the transformer. The first step in the instantiation process is to create two current transformer objects. Once the pertinent current transformers have been instantiated, the "Power_Trans" class constructor proceeds to the three above-described steps in transformer selection, namely, type selection, cooling system selection and verification of electric characteristics. The methods "Select_Transformer_Type", "Select_Cooling_System" and "Verify_Electric_Properties", which belong to the class "Power_Trans", encapsulate the knowledge associated with the above three steps of the transformer selection process. These methods are invoked, in sequence, by the constructor of the class "Power_Trans" in order to instantiate an object of this class and thus accomplish the selection of a power transformer unit.

3.8.3 Electrical Conductors

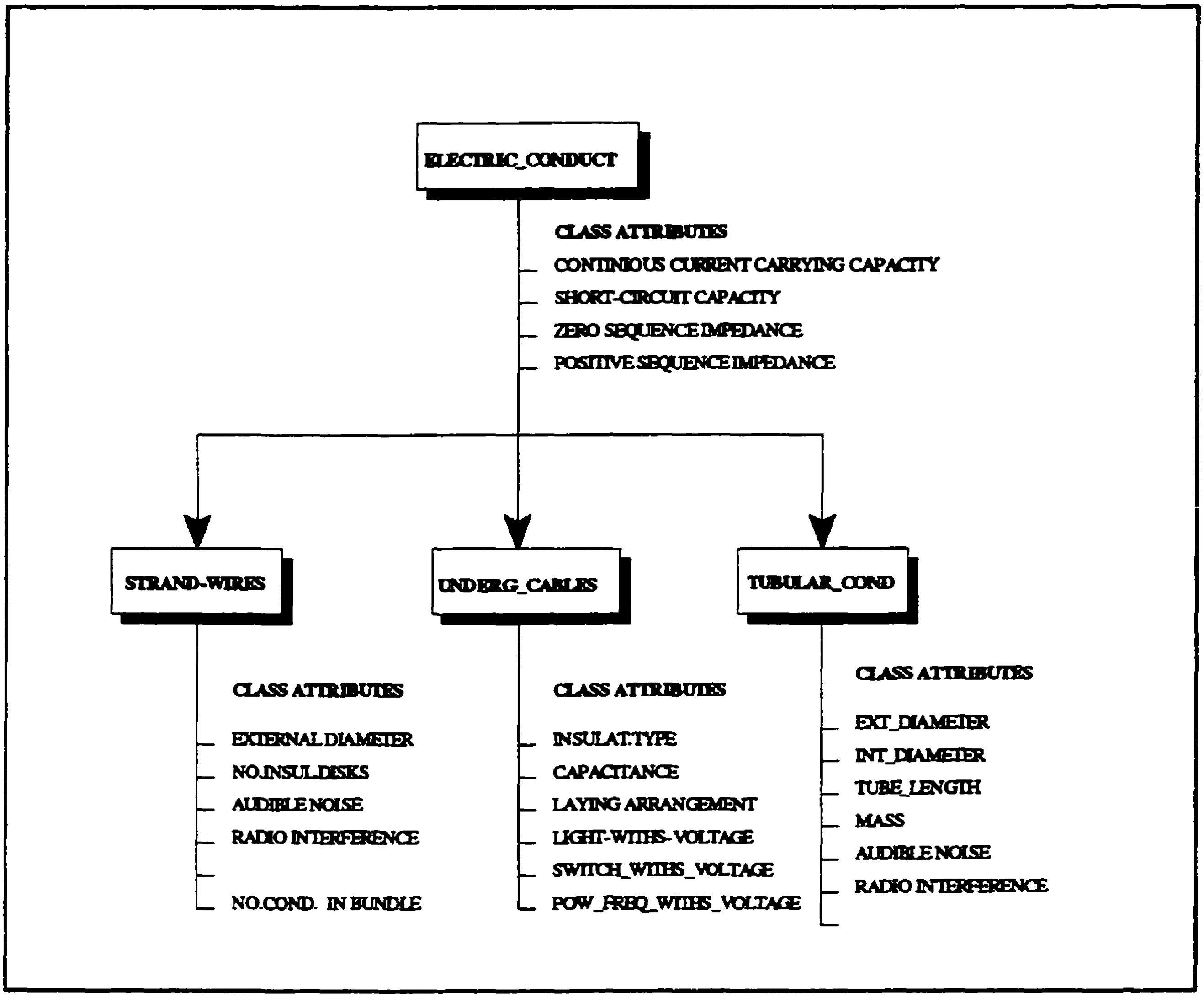

Figure 3.29: Electric conductors class model.

Two kinds of subdivisions are possible to define electrical conductors: according to the type of the conductor and the type of implementation. In the former case it is possible to distinguish three subcategories, namely, overhead stranded-wire conductors, underground cables and tubular conductors. As for the type of implementation, the conductors are mostly used in line terminations and transformer sections to interconnect the pertinent equipment and in substation busbars.

Several factors should be considered when selecting overhead conductors such as the nominal current carrying capacity, the capability to withstand short circuit stresses, the corona effect and atmospheric conditions.The basic properties characterizing stranded-wire conductors are therefore: rated current carrying capacity, positive and zero-sequence impedances, capacitive susceptance, short-duration admissible current (short-circuit capability), conductor diameter, number of conductors per phase and audible noise and radio interference levels. When underground cables are considered, apart from the continuous current-carrying capacity and short-circuit capability, particular properties such as type of insulation withstand voltages, capacitance and laying arrangement must be considered. As for the tubular conductors, typical properties are external and internal diameters, cross-sectional area, mass and tube length. Tubular conductors are often implemented in substation busbar systems.

The object-oriented class hierarchy of electrical conductors is outlined in Figure 3.29. The main class in the hierarchy "Electric_cond" contains the common properties shared by any conductor type. The classes "Underg_cables", Strand_wires" and "Tubular_cond" model underground cables, strand-wire conductors and tubular conductors respectively.

As previously mentioned, the three conductor types can be implemented in different parts of the substation. Moreover, two different types (strand-wire and tubular conductors) can be used in substation busbar systems. Since busbars represent a crucial part of the substation, a detailed description of the busbar conductor selection process is presented in the following paragraphs as an example.

Five types of busbar conductors are considered by SIDE: aluminium and copper tubes, aluminium and copper strand-wire conductors and flat copper busbar conductors. Factors such as nominal operating current, location (indoor, outdoor) and atmospheric conditions are considered in order to decide

Table 3.15: Busbar conductor types.

Busbar Type	Nominal current	Location	Cost	Reliability	Operational flexibility	Environment
TUBE-AL	≥ 2000 A	OUT, IN	9	6	8	5
TUBE-CU	≥ 600 A	OUT, IN	2	6	8	6
WIRE-AL	≥ 800 A	OUT, IN	10	7	3	8
WIRE-CU	≥ 600 A	OUT, IN	2	6	8	6
FLAT	≥ 600 A	IN	5	6	2	7

about the conductor type. However, these factors may not be enough to favour one particular type over another but only serve to recommend a few feasible conductor types. Therefore, multi-criteria analysis should be run in order to enable the choice of the preferred type. The considered criteria are, as usual, the cost, the reliability, the impact on the environment and the operational flexibility. Table 3.15 summarizes the knowledge related to the selection of busbar conductor types and the fixed relative scores. A set of rules which are processed during the type selection has been constructed from the data provided in the Table 3.15. One example of a rule derived form this table is as follows:

IF (*nominal_current* ∈ 2000-2500 A) AND

(*location* = OUTDOOR)

THEN

(*possible_types* = TUBE_AL and TUBE_CU)

The conductor type selection process consists of two steps: (i) to determine a feasible set of conductors through rule processing where the above-mentioned factors (nominal current and location) are used to filter out undesirable conductor types and (ii) to perform multi-criteria analysis in order to choose the most favourable type from the previously reduced set.

Multi-criteria analysis is run based on the relative scores from Table 3.15 as well as on the designer's preferences expressed through the preference weights provided in the design specifications.

The verification of electric properties consists of checking the conductor insulation strength, the current carrying capacity and the capacity to withstand short-circuit thermal stresses. The latter is accomplished through the calculation of the admissible short-circuit value obtained from the following formula [Epri82]:

$$I_{sc} = A * \sqrt{(C*(T+20)/(\rho*t))*\ln((T+t_m)/(T+T_1))} \tag{3.21}$$

here A is the cross-section area, C is the thermal capacity, ρ is specific resistance, t id duration of short-circuit, T_m is maximum admissible temperature, T_i is initial temperature of the conductor and T is a constant which takes the following values: 234.5 for copper and 225 for aluminium conductors.

As an example, after having searched the conductor database in order to extract those conductors which match the previously determined desired type, the following rule is applied to selected cables in order to verify their electric properties:

IF (*lightning_withstand_voltage* ≥ fast-front overvoltage) **AND**
(*Switching_withstand_voltage* ≥ slow-front overvoltage) **AND**
(*power_frequency_withstand_voltage* ≥ temporary overvoltage) **AND**
(*current_carrying_capacity* ≥ nominal current) **AND**
(*Short-circuit capacity* ≥ I_{sc})

THEN (Select Conductor)

Apart from the electric properties which mainly take care of thermal and voltage stresses, the busbar conductors may be also exposed to severe dynamic stresses due to short-circuit faults. In order to ensure that the selected busbars can withstand the expected dynamic stresses, it is necessary to perform a mechanical stress analysis to obtain the required length of the conductor between supports and the spacing between conductors of different phases. This type of mechanical stress analysis was already described in Section 3.6.8.

Where a few conductors from the database meet the above-considered requirements, the one whose current carrying capacity is closest to the expected nominal operating current is chosen.

The object-oriented model of busbar conductors consists of the class "Busbars". As shown in Figure 3.30, this class contains two class members, namely, "Wire_buses" and "Tube_buses" which are instances of the classes "Strand-wires" and Tubular_cond" (Figure 3.29) respectively. Which one of these two will be instantiated depends on the selected bus conductor type. Thus, the first action of the "Busbar" class constructor is to invoke the method "ConductorTypeSelection" in order to come out with the proper conductor type. The next step is to invoke the class constructor of one of the above-mentioned class members which, in turn, invokes the methods "VerifyElectricProperties" and "MechanicalStressAnalysis" to check whether the electric and mechanical characteristics of the conductor meet the specified requirements. Since the latter method belongs to the class "Mechanical_Stresses" which, in turn, belongs to the class "Simulations", the classes "Strand_wires" and

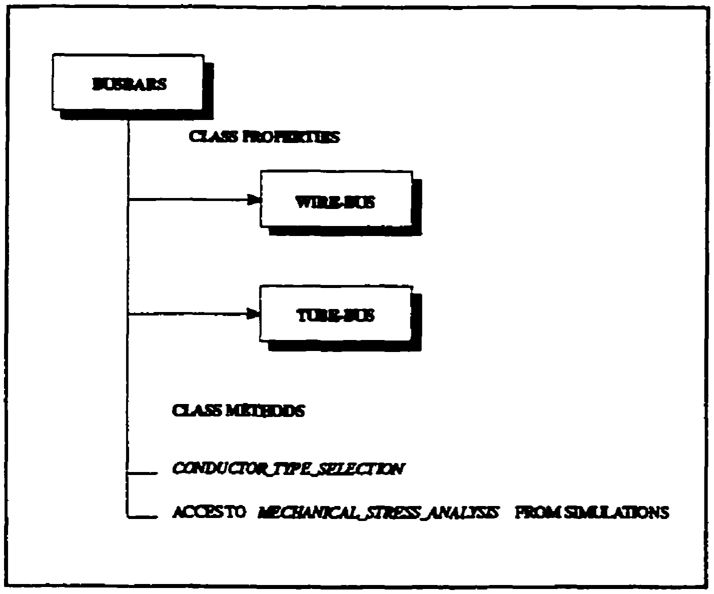

Figure 3.30: Bus conductor class representation.

"Tubular_cond" are declared friends[2] of the class "Mechanical_stresses" so that they can access the method "MechanicalStressAnalysis".

The request for the bus conductor instantiation is placed by the constructor of one of the classes "HV_Busbars" or "LV_Busbars" which model the high-voltage and low-voltage substation busbar systems.

3.8.4 Protection Equipment

Two kinds of protection are considered in electric power networks: protection against overvoltages and protection against short-circuit faults. The former falls under the subject of insulation coordination while the latter is better known as relay protection. Both protection design tasks are based, to a certain extent, on the heuristic knowledge processing and as such are classified by a group of supporting expert systems. The insulation coordination expert system tool has been developed in the course of this research while the development of the expert system for relay protection design still remains a future objective. Thus, the protection electrical equipment considered by SIDE only includes the apparatus employed to accomplish overvoltage protection. The most important members of this category are surge arresters.

Surge arresters are used in substations to protect vital equipment and installations such as power transformers, shunt reactors and underground cables against overvoltages which may occur. Two types of surge arresters are in use, namely, gapped (silicon-carbide) and metal-oxide arresters [ABB88, Sim92, HQM]. The former type responds faster when the sparkover voltage is exceeded

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2

A *friend* class is a class whose methods can access properties of another class to which this class is declared a friend. Similarly, a *friend* function (method) can be declared to a class whose properties this method can normally access.

but the follow current also rises. Furthermore, if a magnetic blow-out facility is not present, this current continues to flow until the next voltage zero crossing. On the other hand, in the case of metal-oxide surge-arresters, the discharge current flows only during the presence of the overvoltage. Metal-oxide arresters are preferred nowadays, particularly in systems with a direct-earthed neutral [Sim92]. They are also good in performing the task of a surge limiter in a cable system when protecting a motor against possible start-up overvoltages [Sim92]. These reasons were enough to justify the consideration of metal-oxide arresters as the main protective devices against overvoltages within SIDE.

The principal properties of surge arresters are lightning and switching protective levels, permanent operating voltage and nominal discharge current. In addition, surge arresters, like other electric apparatus, also possess insulation characteristics such as lightning, switching and power frequency withstand voltage levels.

The selection of surge arresters consists of a relatively simple task. It basically consists of one single rule which verifies whether the arrester's permanent operating voltage can cope with the expected temporary overvoltages at the given location. The rule is contained in the method "VerifyElectricProperties" belonging to the class "Surge_arrest" which, in turn, represents the object-oriented model of surge arresters. As shown in Figure 2.2 (Chapter 2), this class is directly attached to its superclass "Equipment" from which it inherits the most common properties such as cost and failure and repair rates.

3.8.5 Compensation Equipment

Reactive power compensation is an important activity carried out in substations. There exist several grounds for the use of reactive compensation, such as voltage control, power factor correction and stability improvement. The equipment which is involved includes shunt capacitor banks, shunt reactors and series capacitors and more complex devices such as static VAR compensators [Sta86]. The object-oriented class model of electrical apparatus used for reactive compensation purposes is shown in Figure 3.31. The main class "Comps_eq" contains common properties shared by all compensation equipment. These are nominal voltage and nominal reactive power rating.

The classes "Sh.induct", Sh.capac" and "Ser_capac" model the above-mentioned compensation apparatus and, apart from the inherited common properties, they possess their own particular attributes. As for static VAr compensators, their object-oriented model consists of a separate class hierarchy. The main class "SVS" models the standard characteristics of every static VAr system such as the reference voltage (the desired value of operating voltage), the slope of the U-I (voltage-current) characteristic, its overload capability, the response time and audible noise levels. In addition, "SVS" contains class attributes modeling the SVS's basic subcomponents, namely, the coupling transformer (class "CP_trans"), thyristor valves ("Thyr_vl") and the control system ("Ctrl_sys"). The class "SVS" has three subclasses representing the three most common static VAr system configurations. These are the thyristor controlled reactor ("TCR"), the thyristor switched capacitor ("TCS") and a combination of the last two ("TCR+TCS"). Beside the common characteristics inherited from the parent class, each SVS category incorporates its particular subcomponents. For example, as shown in Figure 3.31, the class "TCR" has a class member *SH_I* which is an instance of the class "Sh.induct" modeling a reactor while the class "TCS" contains a member named *SH_C* as an instance of the class "Sh.capac" which represents a capacitor bank.

The instantiation of any of the compensation equipment is triggered by methods from the class modeling the corresponding transformer/compensation constituent group. All the necessary

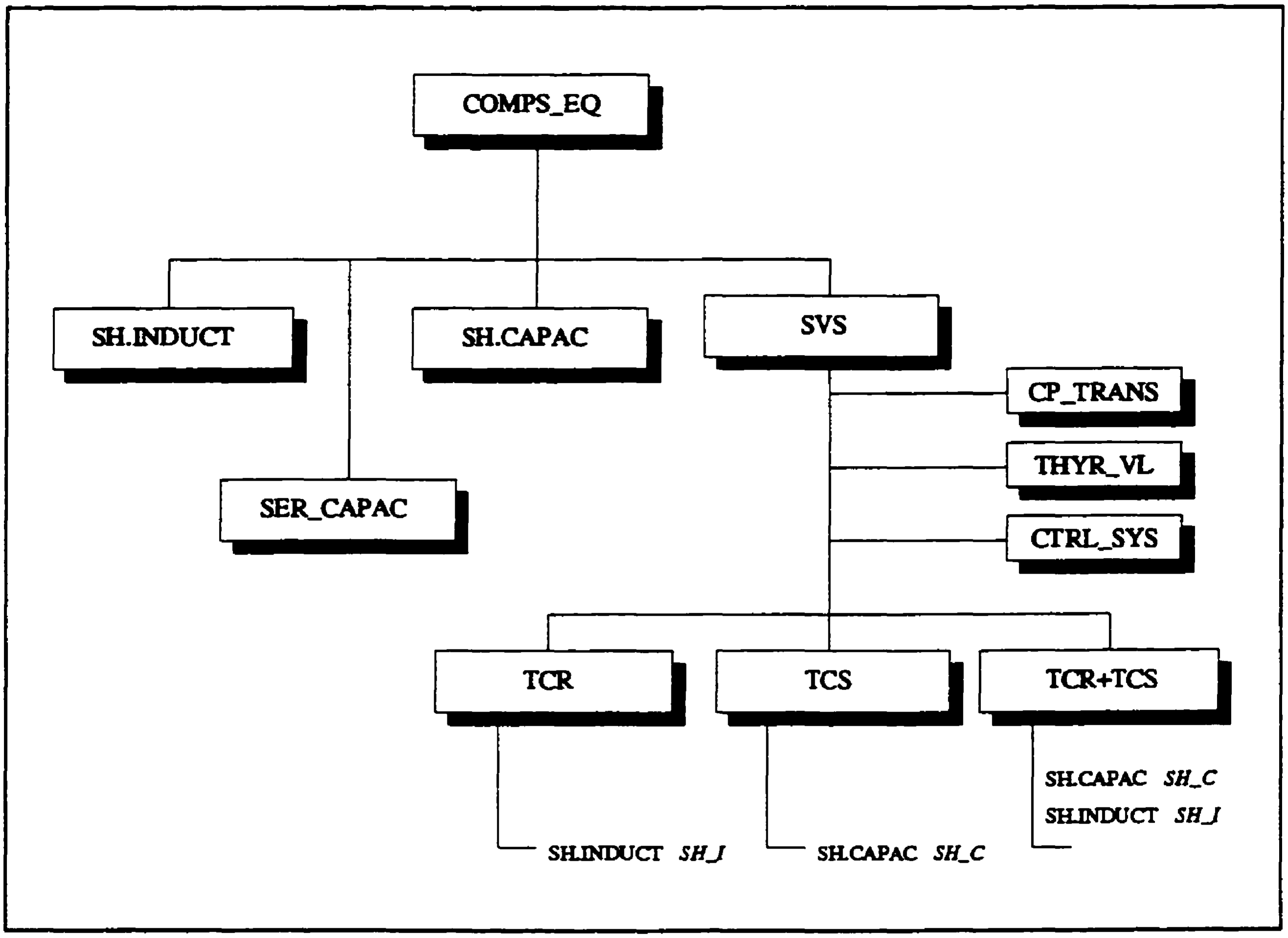

Figure 3.31: Compensation equipment class hierarchy.

information for the compensation equipment selection is obtained from the results of reactive power management simulations preserved in the instance of the class "Reac_mgm" (Section 3.6.4).

3.9 SIDE's Graphical User Interface

A powerful graphical user interface (GUI) has been developed to enable users easy and friendly access to the various SIDE facilities. As mentioned in Section 3.1, the GUI is conceived to be a *client*, that is, a program which allows several users to access SIDE's knowledge and databases as well as various simulation tools at the same time. Moreover, the same user can run more than one session at a time.

SIDE' GUI [Ara94, Ata94] consists mainly of a menu system which is divided as follows:

File. This option manipulates files containing existing design session results, input specifications or graphical representation of various substation components. Standard file operations such as loading, saving, copying, deletion and merging are supported.

*Input.*This option provides user-friendly windows-based forms for entering input specification data. It allows the user to add new input specification records and to modify or delete existing records.

Databases. This option allows the user to browse through the equipment and other databases.

Output. This menu permits the user to access the output results generated by SIDE. The output results are represented in the following forms:

- Graphical, permitting the user to display, examine and modify the complete single-line diagram of the substation as well as to create new graphical symbols for basic electrical equipment and substation composite groups.

- Design report, allowing the user to examine general design information such as the size of the substation (MW), the number of circuits and transformer units, the voltage levels and the substation location.

- Tender document, where the detailed specification of electrical equipment can be found.

- Simulation report, where results of the various simulation studies are stored.

The following are some examples of SIDE's GUI capabilities including the main menu (Figure 3.32), the single-line diagram graphical representation (Figure 3.34), the input specifications entry form (Figure 3.33), and the design window where a user can create new graphical symbols (Figure 3.35). Another very important aspect of the GUI is its explanation facility which offers the user a powerful tool through which one can obtain a detailed explanation about any element or action of SIDE. For example, the user can trace the SIDE process which leads to the selection of a particular electrical apparatus and can also request explanations relating to more sophisticated SIDE activities such as the single-line diagram selection or explanations regarding different kinds of simulations carried out during the design process.

The explanation facility relies on a set of special methods which each class in the model possesses. These methods are called upon during the class object instantiation in order to generate a description of the instantiation process. This description is then stored in special files which are later accessed and read by GUI functions upon a user's request. One example of the explanation facility, namely, the explanation of the circuit-breaker selection process, is now discussed as follows.

As shown in Figure 3.36, the first part of the explanations is related to the selection of the circuit-breaker type. The selection process considers several possible types of circuit breakers and evaluates them in terms of cost, reliability, operational flexibility and impact on the environment. The scores assigned to the circuit breaker alternatives with respect to the four criteria are shown in the first part of the explanation form. The second part of the form reveals the flow of the process related to the selection of the circuit breaker's electrical properties. Thus, it is possible to distinguish steps such as verification of nominal current ratings, short-circuit capacity and insulation levels. In this way it is posssible to add the dimension of explanation to the design process.

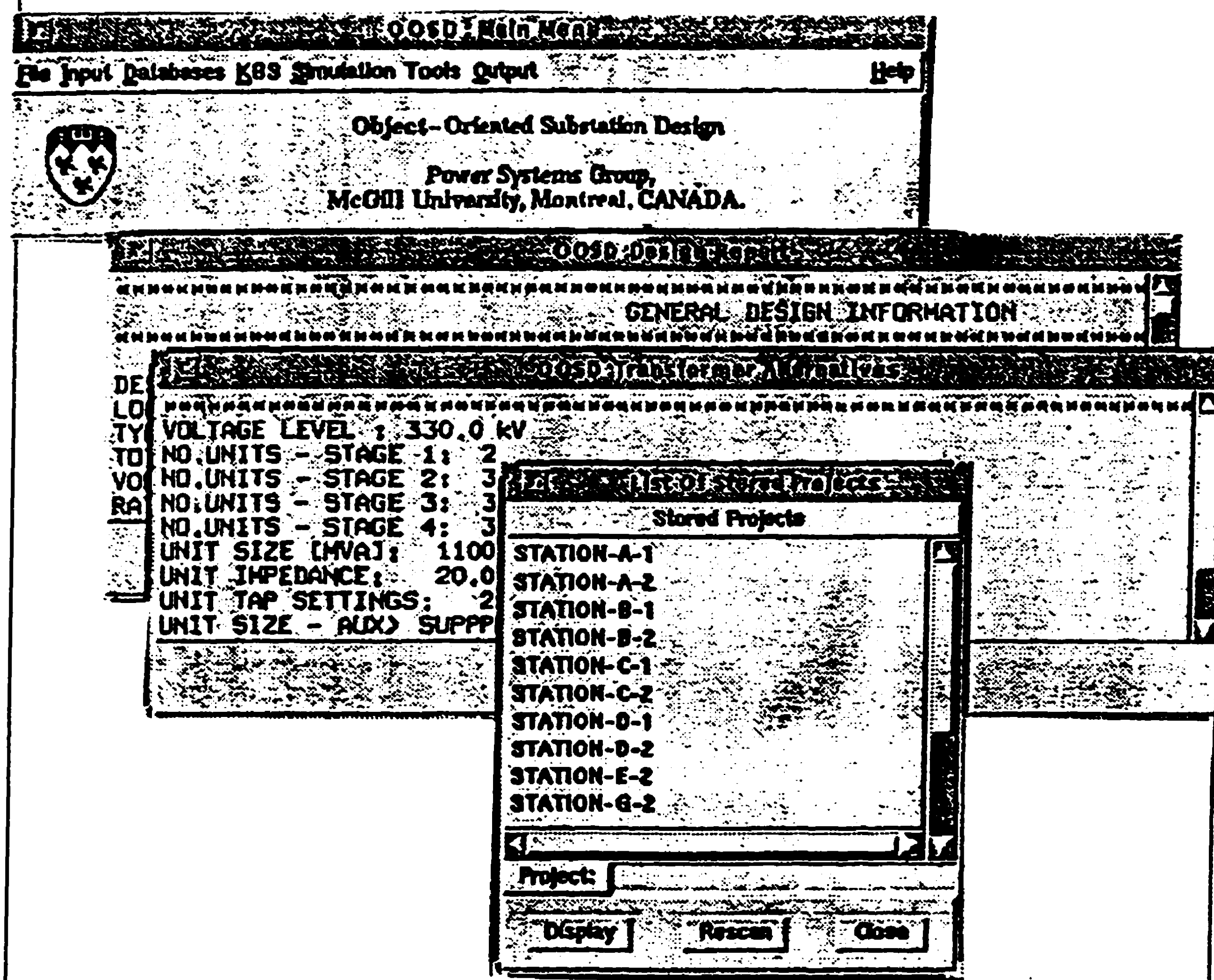

Figure 3.32: SIDE's main menu.

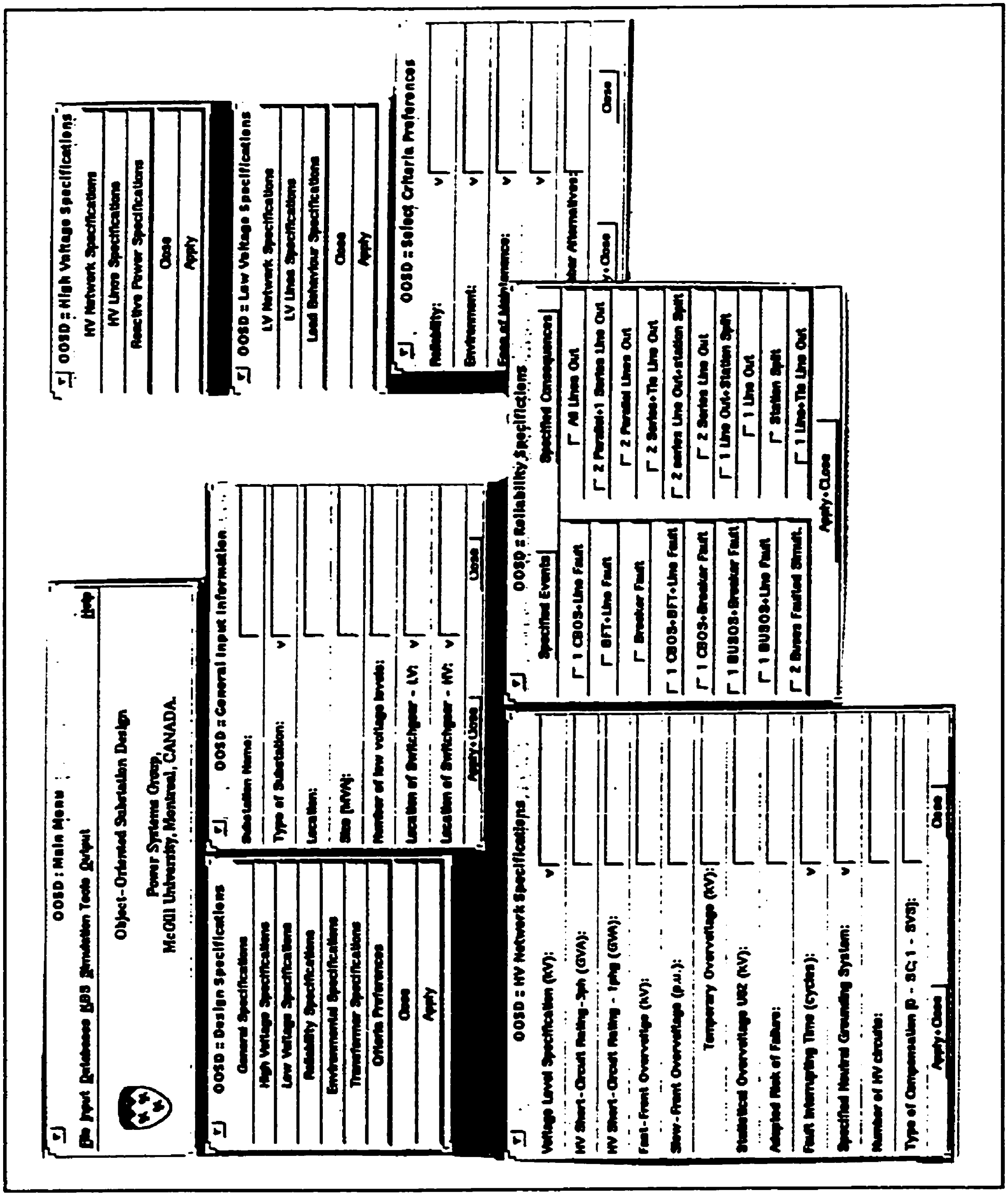

Figure 3.33: The SIDE's input entry form.

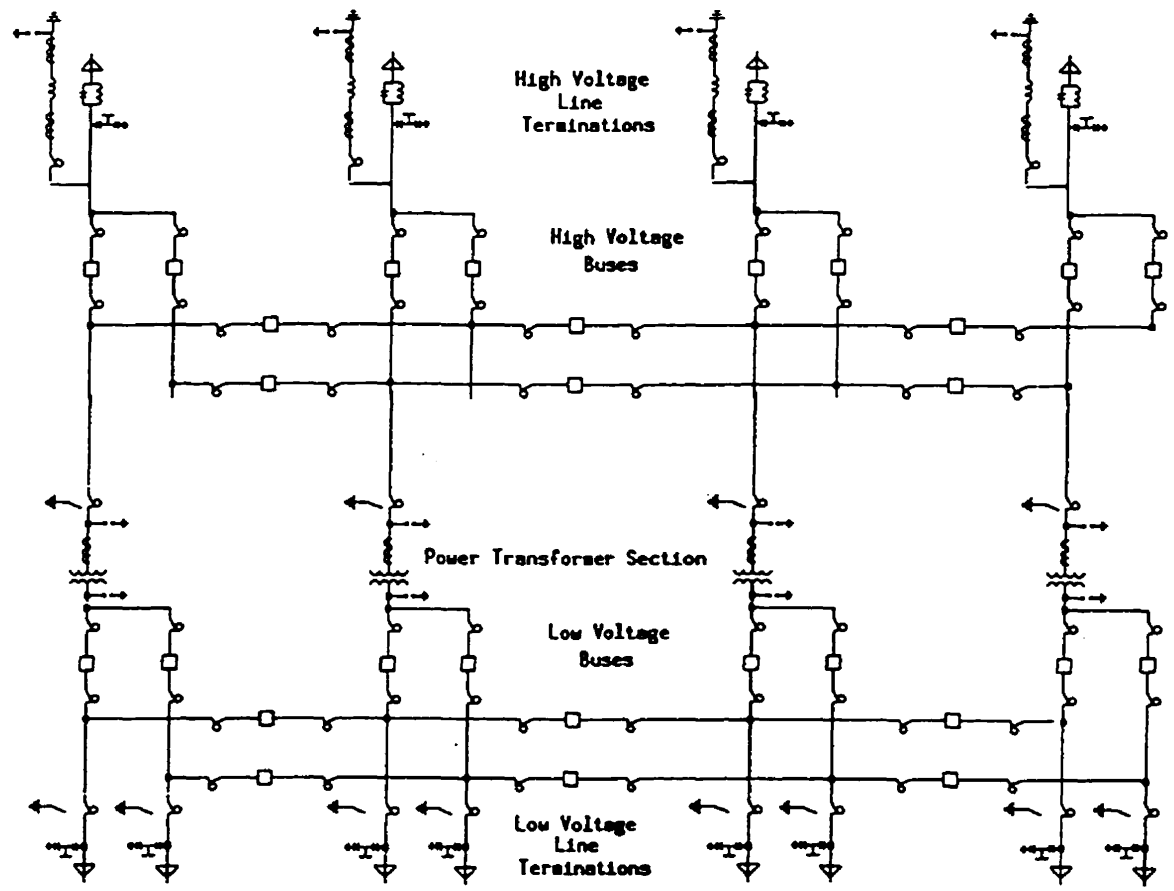

Figure 3.34: An example of SIDE's single-line diagram representation.

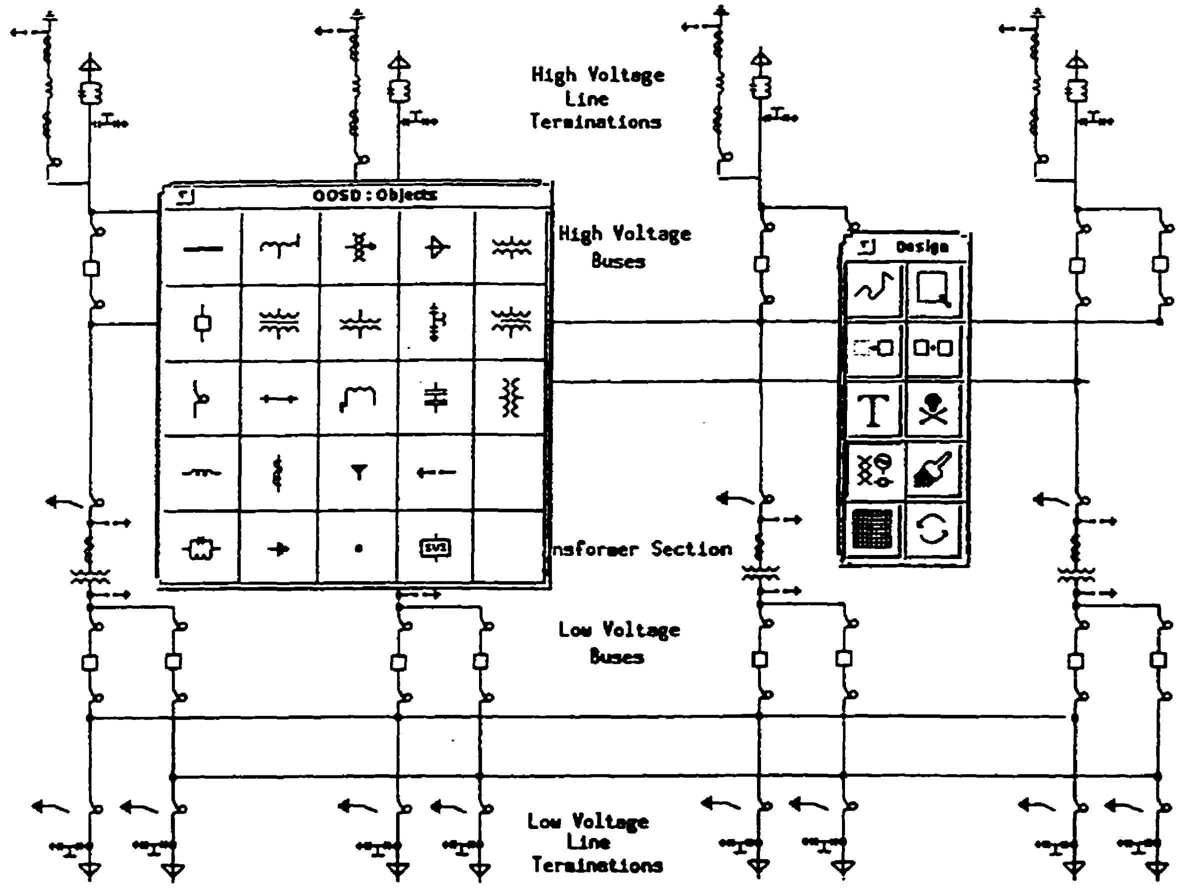

Figure 3.35: An example of the SIDE's design facility.

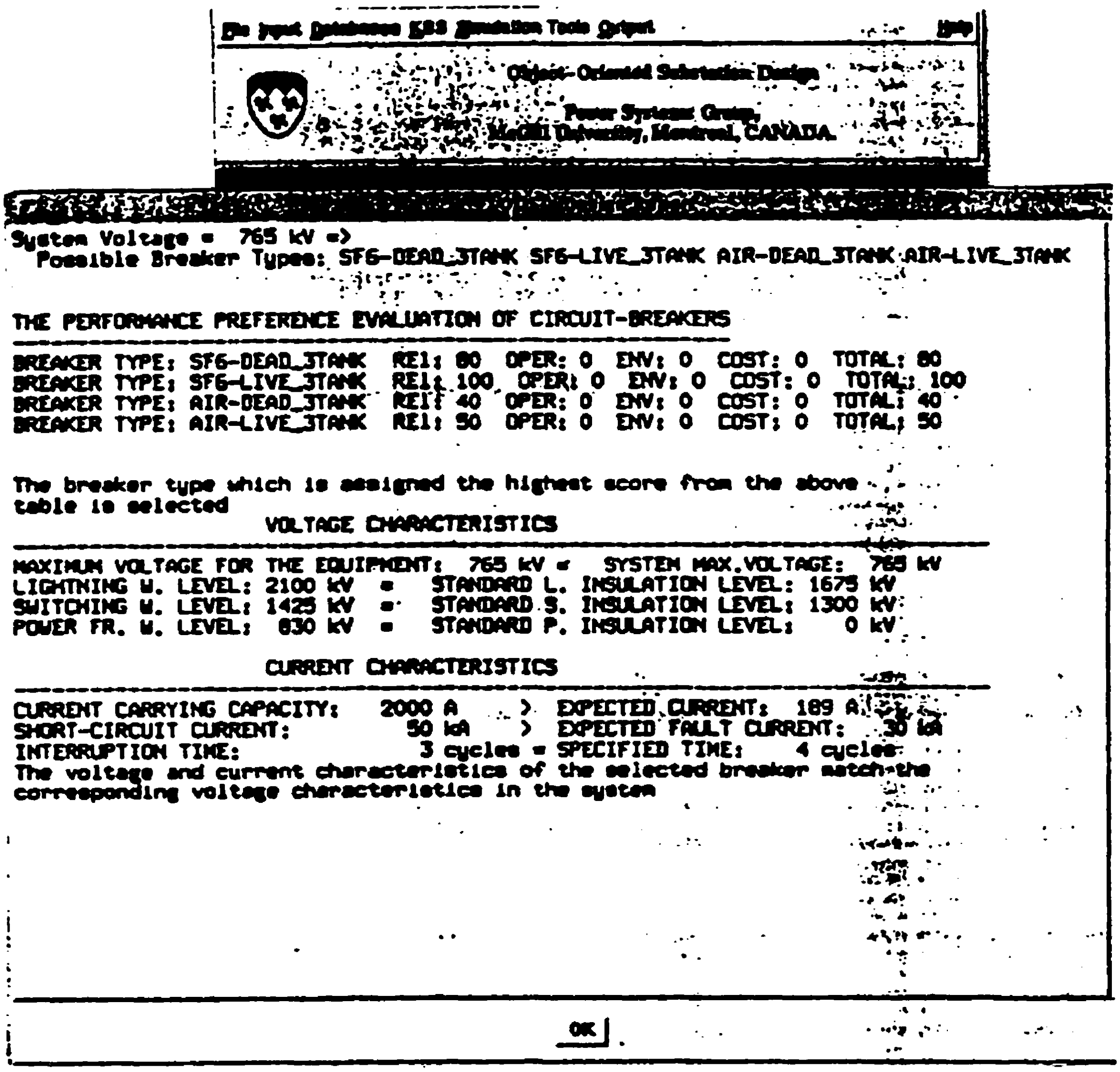

Figure 3.36: An example of SIDE's explanation facility.

4. DESIGN OF SUBSTATIONS USING SIDE

4.1 Summary

The objective of this chapter is to demonstrate that SIDE performs its function as intended, namely, that it is capable of designing substations consistent with existing designs and in a manner satisfactory to human experts. To this end, two distinct practical design cases are studied. The input design specifications characterizing these cases are described first (Section 4.2) including all important data such as power ratings, nominal voltages and insulation levels, short- circuit data, parameters related to incoming and outgoing lines, deterministic reliability criteria and the designer's performance preferences. The corresponding outputs of the design process generated by SIDE are presented in Section 4.3 in the form of:

- General design report
- Single-line diagram
- Results of numerical simulations
- Electrical equipment tender document

The validity and reasonableness of these designs are then discussed and analyzed. In addition, a sensitivity analysis is performed to illustrate how the changes in the user preference weights influence the final designs generated by SIDE.

Finally, in Section 4.4 another validation of SIDE is carried out for a case whose input specifications correspond to those of an existing substation and comparing the design alternatives produced by SIDE with the actual substation.

4.2 Design Specifications

Two sets of design specifications (cases A and B) for the proposed substations are defined in order to demonstrate the capabilities and reasonableness of the results generated by SIDE. In both cases tested, the power and voltage ratings, the environmental constraints, and the insulation and other power network characteristics are common. The major differences in the design specifications of cases A and B occur in the deterministic reliability criteria and in the user preference weights as these are the most likely criteria to vary in practical situations. The input specifications are provided in Tables 4.1 and 4.2 for case A and B respectively.

Case A places 100 percent user preference on reliability and zero percent on the other weights. Thus this case will tend to be more costly (and more reliable) than case B. To ensure this reliability, the list of unacceptable consequences (due to various adverse events) is quite extensive. By unacceptable is usually meant a consequence which results in load curtailement. To prevent such consequences, the arrangement of the substation equipment, as refleceted in the single-line diagram, must be suchc as to ensure this design requirement.

Case B places 100 percent user preference on cost and zero percent on the other weights. As a result, this case will produce a much less extensive substation but with lower reliability. The list of unacceptable consequencesis much reduced as compared to case A. In other words, consequences that involve load curtailement are deemed acceptable and this is also refleceted in the single-line diagram which is much simpler than in case A.

One might consider that case B includes all possible cases so it is more difficult to find the least expensive one. On the other hand, case A, being only a subset of case B with more restrictionswill lend itself more easily to practical solutions. In other words, the security region of case B is much larger than for case A since it includes more acceptable consequences, albeit with possible load curtailement.

These considerations are depicted in Figure 4.1. It is evident that the ideal solution for either case rests in its corresponding security boundary.

In the present exercice, securityis defined as the ability of the design to cope with adverse events whith either involving load curtailement (case B) or no load curtailement (case A).

In a further application of this methoology, one may be able to take load curtailement into account through some probabilistic penalties but at the moment only a deterministic view of reliability is presented.

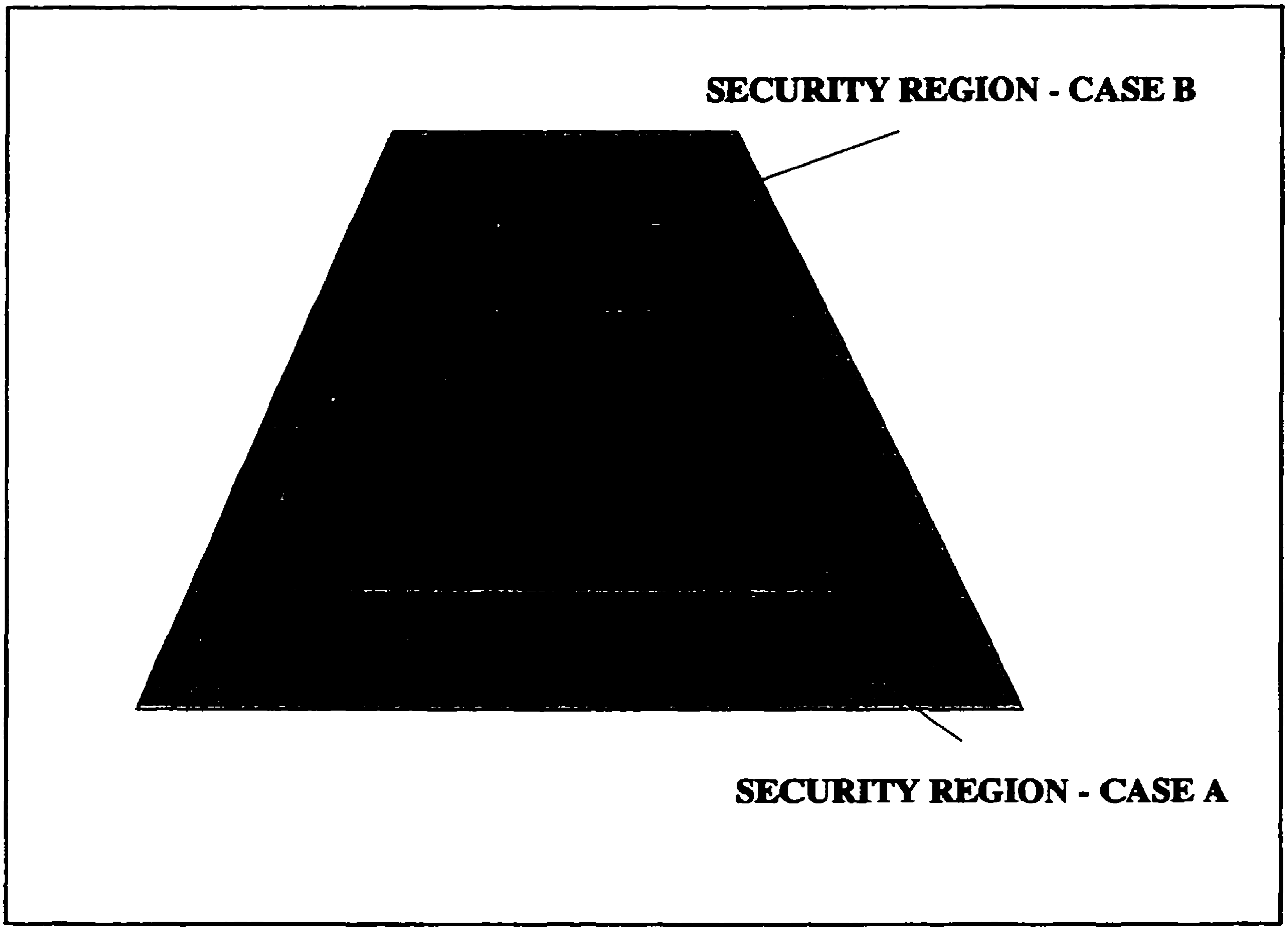

Figure 4.1: SIDE solutions security considerations.

Table 4.1: Design specifications for case A.

INPUT SPECIFICATIONS - CASE A	
Voltage Levels (kV)	**Insulation Levels**
735/315	Maximum system voltage : 765/330 kV phase-to-phase Lightning impulse: 2100/1300 kV crest phase-to-ground Switching impulse: 1550/950 kV crest phase-to-ground Temporary overvoltage: 1.5/1.5 per unit Surge arrester rating: 470/206 kV phase-to-ground Lightning impulse for protected equipment: 1950/1175 kV Minimum air clearance to earth: 5/2.5 meters Minimum air clearance between phases: 8.5 /4 meters
Power Rating (MVA)	
4000	
Short-Circuit Data	
Short-circuit level: 40 GVA Fault duration: 6 cycles	**Reliability Criteria** (Defined in Section 3.5)

Incoming Line Data	**Credible Events**	**Consequences**
Number of lines: 4 Rating of lines: 2500 MVA	CBOOS + LF √	ALL LINES √
Outgoing Line Data	LF + BFT √	2 PARL. + 1 SERL √
Number of lines: 8 Rating of lines: 1000 MVA	CBOOS + LF + BFT	2 PARL √
Costs	CBOOS + BF	2 SERL + TIEL √
Cost of losses: 4000 $/kW Cost of energy not delivered: 400 $/MWh	BUSOS + BF	2 SERL + ST_SPLIT √
	BUSOS + LF	2 SERL √
	2BUSF	1 LINE + TIEL
		1 LINE + ST_SPLIT
		1 LINE
		ST_SPLIT

User Preference Weights	
Environmental impact: 0%	Reliability: 100%
Cost: 0%	Operational flexibility: 0%

NB: Unacceptable consequences and specified credible events are indicated by a check (√)

Table 4.2: Design specifications for case B.

<table>
<tr><th colspan="3">INPUT SPECIFICATIONS - CASE B</th></tr>
<tr><th>Voltage Levels (kV)</th><th colspan="2">Insulation Levels</th></tr>
<tr><td>735/315</td><td colspan="2" rowspan="4">Maximum system voltage : 765/330 kV phase-to-phase
Lightning impulse: 2100/1300 kV crest phase-to-ground
Switching impulse: 1550/950 kV crest phase-to-ground
Temporary overvoltage: 1.5/1.5 per unit
Surge arrester rating: 470/206 kV phase-to-ground
Lightning impulse for protected equipment: 1950/1175 kV
Minimum air clearance to earth: 5/2.5 meters
Minimum air clearance between phases: 8.5 /4 meters</td></tr>
<tr><th>Power Rating (MVA)</th></tr>
<tr><td>4000</td></tr>
<tr><th>Short-Circuit Data</th></tr>
<tr><td>Short-circuit level: 40 GVA
Fault duration: 6 cycles</td><th colspan="2">Reliability Criteria (Defined in Section 3.5)</th></tr>
<tr><th>Incoming Line Data</th><th>Credible Events</th><th>Consequences</th></tr>
<tr><td>Number of lines: 4
Rating of lines: 2500 MVA</td><td rowspan="5">CBOOS + LF √
LF + BFT √
CBOOS + LF + BFT
CBOOS + BF
BUSOS + BF
BUSOS + LF
2BUSF</td><td rowspan="5">ALL LINES √
2 PARL. + 1 SERL
2 PARL
2 SERL + TIEL
2 SERL + ST_SPLIT
2 SERL
1 LINE + TIEL
1 LINE + ST_SPLIT
1 LINE
ST_SPLIT</td></tr>
<tr><th>Outgoing Line Data</th></tr>
<tr><td>Number of lines: 8
Rating of lines: 1000 MVA</td></tr>
<tr><th>Costs</th></tr>
<tr><td>Cost of losses: 4000 $/kW
Cost of energy not delivered: 400 $/MWh</td></tr>
<tr><th colspan="3">User Preference Weights</th></tr>
<tr><td colspan="2">Environmental impact: 0%</td><td>Reliability: 0%</td></tr>
<tr><td colspan="2">Cost: 100%</td><td>Operational flexibility: 0%</td></tr>
</table>

NB: Unacceptable and specified credible events are indicated by a check (√)

4.2.1 Power System Criteria

• The substation to be designed is described as a transformer substation whose purpose is to supply 315 kV sub-transmission circuits from a 735 kV grid. The rating of the substation is 4000 MVA and this load is carried over four 315 kV double-circuit lines where each circuit is rated 1000 MVA.

•The short-circuit levels and insulation levels specified from system studies and insulation coordination are as shown in Tables 4.1 and 4.2.

• Variations in the supply voltage are expected to lie in the range of plus-minus five percent.

4.2.2. Deterministic Reliability Criteria

The specified credible events and unacceptable consequences for cases A and B are shown in Tables 4.1 and 4.2 respectively. In case A, this specification requires that the occurrence of any of the considered credible events should not entail any consequence involving two parallel lines out of service. This severe requirement does not apply in case B where only the outage of a complete substation is considered unacceptable. Thus, case B is more tolerant to outages and should result in a less robust design.

4.2.3. Environmental Criteria

• The substation is located outdoors in a rural area assuming relatively normal climatic conditions for the 44th parallel (temperature range between -50 and 40 °C, altitude above sea level below 1000 m, wind, snowfall and rainfall conditions are also within normal ranges).

• The bus conductors on the 735 kV and 315 kV sides must respect the specified levels for audible noise and radio interference generally accepted as standard, for example 60 dB and 67 dB respectively.

4.2.4 User Preference Weights

As shown in Tables 4.1 and 4.2, the criteria related to reliability is given the highest priority in case A while the investment cost is the most important criterion in case B. Apart from these two basic cases, a variety of cases involving different values of preference weights is also considered as summarized in Table 4.3 in order to examine the sensitivity of the designs with respect to the criteria emphasized by the user.

Table 4.3: Variations in user preference weights.

Case / Criteria	Cost (%)	Reliability (%)	Flexibility (%)	Environment (%)
A-1 , B-1	0	100	0	0
A-2 , B-2	100	0	0	0
A-3 , B-3	0	0	100	0
A-4 , B-4	0	0	0	100
A-5 , B-5	50	20	20	10
A-6 , B-6	30	20	40	10
A-7 , B-7	10	50	30	10
A-8 , B-8	10	10	30	50

4.3 Outputs of the Design Process

The outputs of the SIDE design process are presented in this section. The general design information related to cases A and B is shown in Tables 4.4 and 4.5 respectively. In addition to the basic data concerning the voltage levels, power ratings, type and location of the substation, the general design information also depicts the single-line diagram configurations of the substation (HV and LV busbar arrangements). Tables 4.6 and 4.7 present the more important simulation results (insulation coordination, short-circuit calculations, transformer preliminary analysis and cost evaluation) for cases A and B respectively.

Table 4.4: General design information - case A.

DESIGN TITLE:	CASE - A	
TYPE OF SUBSTATION:	TRANSFORMER - RURAL	
POWER RATING:	4000 MVA	
VOLTAGE LEVEL:	HIGH VOLTAGE	LOW VOLTAGE
VOLTAGES:	735 kV	315 kV
NUMBER OF CIRCUITS:	4	8
LOCATION:	OUTDOOR	OUTDOOR
BUSBAR ARRANGEMENTS		
ALTERNATIVE - 1	DOUBLE BUSES WITH SECT.	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 2	DOUBLE BUSES WITH SECT.	DOUBLE BUSES
ALTERNATIVE - 3	BREAKER-AND-A-HALF	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 4	BREAKER-AND-A-HALF	DOUBLE BUSES
ALTERNATIVE - 5	DOUBLE BUSES	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 6	DOUBLE BUSES	DOUBLE BUSES

Table 4.5: General design information - case B.

DESIGN TITLE:	CASE - B	
TYPE OF SUBSTATION:	TRANSFORMER - RURAL	
POWER RATING:	4000 MVA	
VOLTAGE LEVEL:	HIGH VOLTAGE	LOW VOLTAGE
VOLTAGES:	735 kV	315 kV
NUMBER OF CIRCUITS:	4	8
LOCATION:	OUTDOOR	OUTDOOR
BUSBAR ARRANGEMENTS		
ALTERNATIVE - 1	DOUBLE BUSES	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 2	DOUBLE BUSES	DOUBLE BUSES
ALTERNATIVE - 3	DOUBLE BUSES	SINGLE BUSES
ALTERNATIVE - 4	DOUBLE BUSES WITH SECT.	SINGLE BUSES
ALTERNATIVE - 5	BREAKER-AND-A-HALF	DOUBLE BUSES
ALTERNATIVE - 6	DOUBLE BUSES WITH SECT.	DOUBLE BUSES

Table 4.6: Simulation results - case A.

TRANSFORMER ANALYSIS		SHORT-CIRCUIT CALCULATIONS	
NUMBER OF UNITS:	4	THREE-PHASE FAULT - HV:	30 kA
UNITS SIZE:	840 / 1120 / 1400 MVA	THREE-PHASE PEAK - HV :	51 kA
UNIT IMPEDANCE:	12 %	THREE-PHASE FAULT - LV :	29 kA
TAP CHANGER:	2 x 2.5 %, -2 x 2.5 %	THREE-PHASE PEAK - LV :	43 kA
INSULATION COORDINATION		**COST EVALUATION**	
		ALTER.	COST ($)
PHASE-TO-GROUND - 735 kV			
MAXIMUM VOLTAGE:	765 kV	ALT-1	79029600
LIGHTNING WITHS. VOLTAGE:	1950 kV	ALT-2	75429600
SWITCHING WITHSTAND VOLTAGE:	1550 kV	ALT-3	76829600
		ALT-4	73229600
		ALT-5	76829600
PHASE-TO-GROUND - 315 kV		ALT-6	73229600
MAXIMUM VOLTAGE:	330 kV		
LIGHTNING WITHSTAND VOLTAGE:	1175 kV		
SWITCHING WITHSTAND VOLTAGE:	950 kV		

Table 4.7: Simulation results - case B.

TRANSFORMER ANALYSIS		SHORT-CIRCUIT CALCULATIONS	
NUMBER OF UNITS:	4	THREE-PHASE FAULT - HV:	30 kA
UNITS SIZE:	840 / 1120 / 1400 MVA	THREE-PHASE PEAK - HV :	51 kA
UNIT IMPEDANCE:	12 %	THREE-PHASE FAULT - LV :	29 kA
TAP CHANGER:	2 x 2.5 %, -2 x 2.5 %	THREE-PHASE PEAK - LV :	43 kA
INSULATION COORDINATION		**CSOT EVALUATION**	
PHASE-TO-GROUND - 735 kV		ALTER.	COST ($)
MAXIMUM VOLTAGE:	765 kV	ALT-1	58346640
LIGHTNING WITHS. VOLTAGE:	1950 kV	ALT-2	55947000
SWITCHING WITHSTAND VOLTAGE:	1550 kV	ALT-3	52350000
		ALT-4	61945000
PHASE-TO-GROUND - 315 kV		ALT-5	63100000
		ALT-6	63980000
MAXIMUM VOLTAGE:	330 kV		
LIGHTNING WITHSTAND VOLTAGE:	1175 kV		
SWITCHING WITHSTAND VOLTAGE:	950 kV		

4.3.1 Selection of Single-line Diagrams

Comparing the results corresponding to cases A and B, it is evident that busbar arrangements characterized by a high level of reliability are selected in case A (double buses with/without sectionalizing breakers) while the preferred choices in case B are the less reliable options (single bus). These differences are mostly due to the specified deterministic reliability criteria and, to some extent, to the chosen user preference weights.

As discussed in Chapter 3, the selection of busbar arrangements represents the core process in establishing the substation single-line diagram configuration. A good example is the selection of busbar arrangements for the six design alternatives generated for case A. As can be observed in Table 4.5, the combinations of only three different arrangements (double buses with and without sectionalizing breakers and the breaker-and-a-half arrangement) constitute the six design alternatives of case A. These arrangements have been retained from the starting set consisting of six basic busbar configurations. As explained in Chapter 3, the first filter eliminated those busbars which are not practical for the specified system voltages. Thus, single-bus and ring-buses were filtered out as potential candidates for the 765 kV side. Similarly, when the 330 kV voltage level is considered, the ring-bus arrangements are omitted as inappropriate. The next filter examined the remaining set with respect to the deterministic reliability criteria and as a result of this analysis the single busbar arrangement was removed from the 330 kV feasible set as a result of the severe deterministic criteria imposed. The last selection filter has removed the breaker-and-a-half arrangement from the 330 kV set since the available space was not sufficient to accommodate this arrangement. The next step in the selection process was to rank the retained arrangements according to the specified user preference weights. Hence, since the reliability criterion was given a 100% preference, the arrangements were ordered as follows:

High Voltage (765 kV): **Double buses with sect., Breaker-and-a-half, Double buses**
Low voltage (330 kV): **Double buses with sect., Double buses**

Finally, the last activity in the single-line diagram selection process was to combine the above chosen arrangements with other substation composite parts in order to construct the complete single-line diagrams, examples of which are shown in Figures 4.1a and 4.1b for cases A and B respectively.

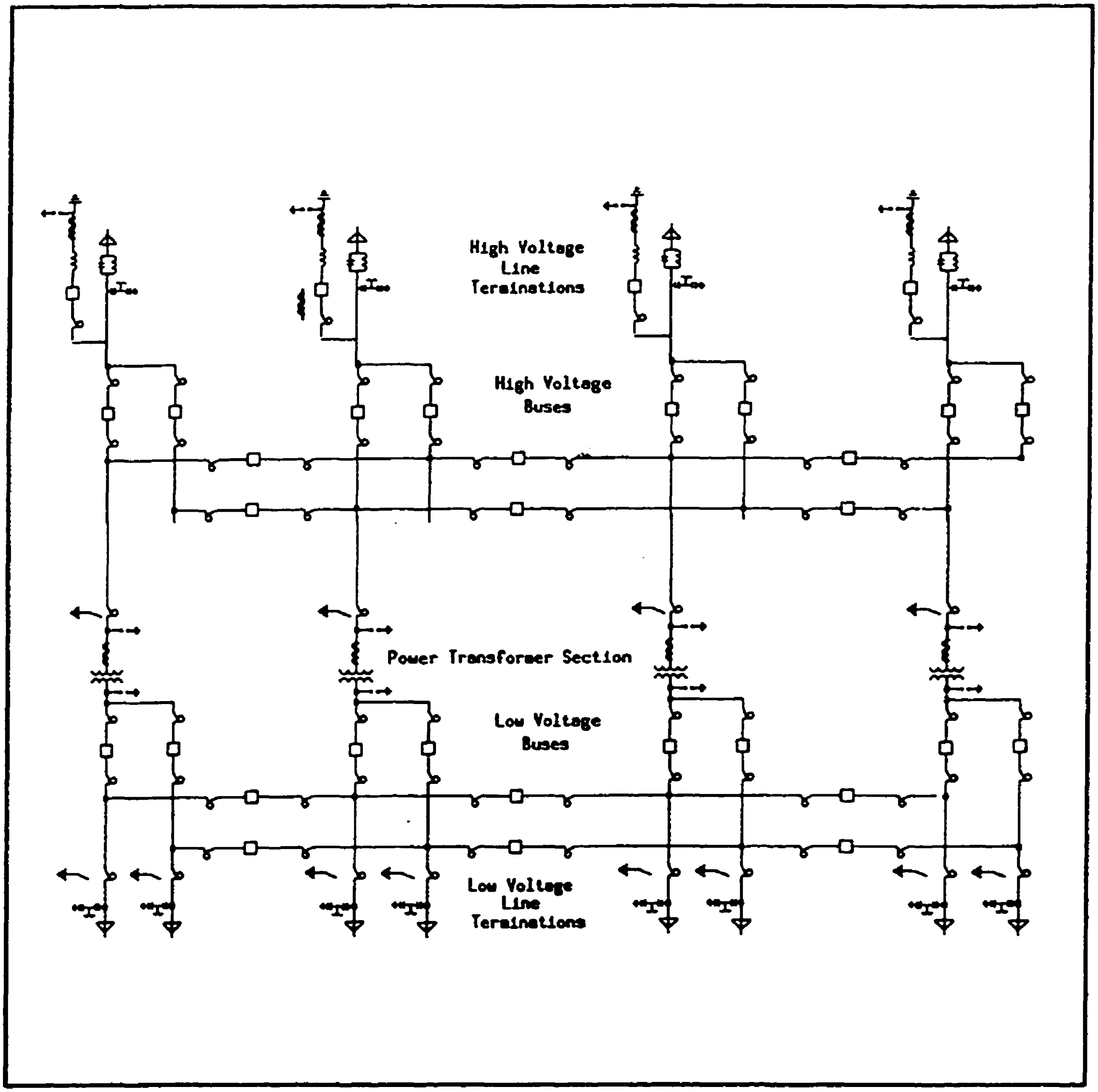

Figure 4.1a: Substation single-line diagram - case A.

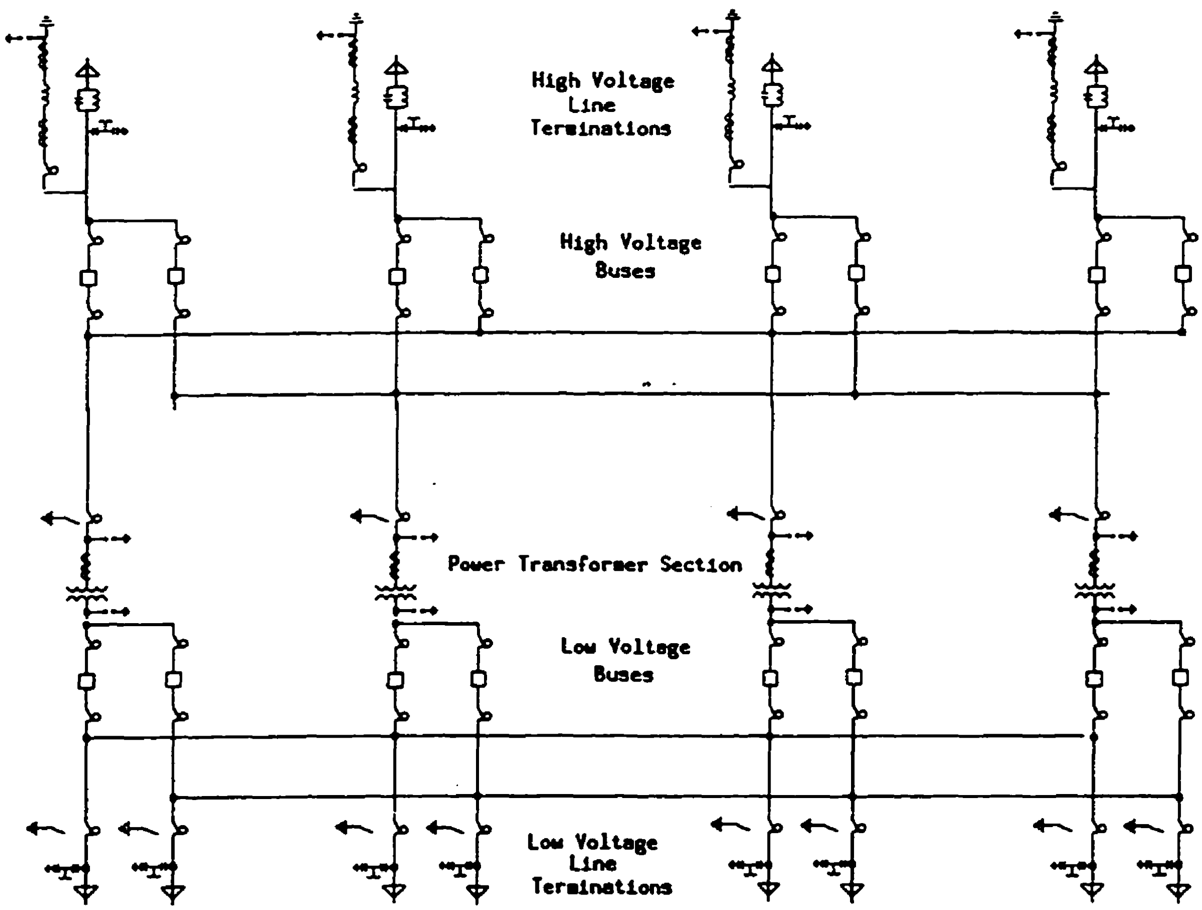

Figure 4.1b: Substation single-line diagram - case B:

4.3.2 Selection of Electrical Equipment

Apart from the single-line diagram, another important task in substation design is the selection of electrical equipment. This process basically consists of equipment type selection and verification of electrical properties. A good example of this process is the selection of the substation high-voltage circuit breakers. As shown in Table 4.8, the feasible circuit-breaker types are first determined based on the voltage level (765 kV) and the substation location (outdoors). The ranking of possible circuit breakers is accomplished next according to the scores calculated using multi-criteria analysis where user preference weights are combined with relative scores (Table 3.7). Thus, based on the selected user preferences (cost, 10%, reliability, 30%, operational flexibility, 10% and environmental impact,

Table 4.8: Selection of substation high voltage circuit breakers.

SYSTEM VOLTAGE:	765 kV				
SUBSTATION LOCATION:	OUTDOORS				
FEASIBLE BREAKER TYPES:	SF6, AIR BLAST.				
MULTI-CRITERIA EVALUATION					
TYPE	RELIABILITY	OPER. FLEX.	ENVIR. IMPACT	COST	TOTAL
SF6	3 * 10 pts.	1 * 9 pts.	5 * 7 pts.	1 * 4 pts	78 pts.
AIR BLAST	3 * 4 pts.	1 * 7 pts.	5 * 10 pts.	1 * 2 pts.	71 pts.
MINIMUM OIL	-	-	-	-	-
BULK OIL	-	-	-	-	-

ELECTRICAL PROPERTIES - VOLTAGE		
PROPERTY	CIRCUIT BREAKER	SYSTEM
MAX.VOLTAGE:	765 kV	765 kV
LIGHTNING W. LEVEL:	2100 kV	1675 kV
SWITCHING W. LEVEL:	1425 kV	1300 kV
ELECTRICAL PROPERTIES - CURRENT		
PROPERTY	CIRCUIT BREAKER	SYSTEM
NOMINAL CURRENT:	2000 A	755 A
SHORT-CIRCUIT:	50 kA	30 kA

Table 4.9a: Tender document summary - case A.

HIGH VOLTAGE LINE TERMINATIONS				
BREAKERS SF6-LIVE-3TANK 765 kV, 2000 A NUMBER: 4 1120000 $	DISCONNECTORS 765 kV, 2000 A NUMBER: 8 109000 $	CTS SINGLET-MIN-OIL 765 kV, 2000 A NUMBER: 12 109000 $	PTS CAPACITIVE 765 kV NUMBER: 4 167000 $	ARRESTERS 470 kV, 20 kA NUMBER: 4 90000 $
HIGH VOLTAGE BUSES				
BREAKERS SF6-LIVE-3TANK 765 kV, 4000 A NUMBER: 14 1090000 $	DISCONNECTORS 765 kV, 4000 A NUMBER: 28 109000 $	CTS SINGLET-MIN-OIL 765 kV, 4000 A NUMBER: 14 109000 $	BUSES AL. TUBES AND CONDUCTORS, 765 kV, 4000 A 500 $/m	
TRANSFORMER SECTION				
BREAKERS	DISCONNECTORS 765 kV, 2000 A 330 kV, 2000 A NUMBER: 4, 4 109000 $, 46000 $	CTS WOUND-MIN-OIL 765 kV, 330 kV, 2000 A NUMBER: 4, 4 109000 $, 96000 $	TRANSFORMERS OIL-SINGLE-AUTO 765/330 kV, 840/1120/1400 MVA 7000000 $	ARRESTERS 470 kV, 20 kA 206 kV, 10 kA NUMBER: 4, 4 90000 $, 9000 $
LOW VOLTAGE BUSES				
BREAKERS SF6-LIVE-3TANK 330 kV, 2000 A NUMBER: 14 493000 $	DISCONNECTORS 330 kV, 2000 A NUMBER: 28 46000 $	CTS SINGLET-MIN-OIL 330 kV, 2000 A NUMBER: 14 46000 $	BUSES AL. TUBES AND CONDUCTORS, 330 kV, 4000 A 500 $/m	
LOW VOLTAGE LINE TERMINATIONS				
	DISCONNECTORS 330 kV, 2000 A NUMBER: 8 46000 $		PTS INDUCTIVE-1-OIL 330 kV NUMBER: 8 81000 $	

50%), the SF6-Live_Tank breakers were chosen. Once the breaker type has been determined, the voltage-related properties (rated voltage, insulation levels) and current-related properties (rated and short-circuit capacity) are chosen such that the selected circuit breaker can withstand prescribed

Table 4.9b: Tender document summary - case B.

HIGH VOLTAGE LINE TERMINATIONS				
BREAKERS	DISCONNECTORS	CTS	PTS	ARRESTERS
	765 kV, 2000 A NUMBER: 8 109000 $	SINGLET-MIN-OIL 765 kV, 2000 A NUMBER: 8 109000 $	CAPACITIVE 765 kV NUMBER: 4 167000 $	470 kV, 20 kA NUMBER: 4 90000 $
HIGH VOLTAGE BUSES				
BREAKERS	DISCONNECTORS	CTS	BUSES	
SF6-LIVE-3TANK 765 kV, 4000 A NUMBER: 8 1090000 $	765 kV, 4000 A NUMBER: 16 109000 $	SINGLET-MIN-OIL 765 kV, 4000 A NUMBER: 8 109000 $	AL. TUBES AND CONDUCTORS, 765 kV, 4000 A 500 $/m	
TRANSFORMER SECTION				
BREAKERS	DISCONNECTORS	CTS	TRANSFORMERS	ARRESTERS
	765 kV, 2000 A 330 kV, 2000 A NUMBER: 4, 4 109000 $, 46000 $	WOUND-MIN-OIL 765 kV, 330 kV, 2000 A NUMBER: 4, 4 109000 $, 96000 $	OIL-SINGLE-AUTO 765/330 kV, 840/1120/1400 MVA 7000000 $	470 kV, 20 kA 206 kV, 10 kA NUMBER: 4, 4 90000 $, 9000 $
LOW VOLTAGE BUSES				
BREAKERS	DISCONNECTORS	CTS	BUSES	
SF6-LIVE-3TANK 330 kV, 2000 A NUMBER: 8 493000 $	330 kV, 2000 A NUMBER: 16 46000 $	SINGLET-MIN-OIL 330 kV, 2000 A NUMBER: 8 46000 $	AL. TUBES AND CONDUCTORS, 330 kV, 4000 A 500 $/m	
LOW VOLTAGE LINE TERMINATIONS				
	DISCONNECTORS		PTS	
	330 kV, 2000 A NUMBER: 8 46000 $		INDUCTIVE-1-OIL 330 kV NUMBER: 8 81000 $	

operating conditions.

The main result of the equipment selection process is the so-called design tender document which consists of the equipment design specification including the cost and quantity of each electrical component. The tender documents corresponding to the single-line diagram for cases A and B are shown in Tables 4.9a and 4.9b respectively.

4.3.3 Sensitivity Analysis

As for the user preference weights, their impact on the final design alternatives has been examined through a sensitivity analysis where three aspects of the design are particularly considered, namely, the selection of the single line diagram, the selection of major substation equipment and the overall evaluation of design alternatives. The results of this analysis are presented in Tables 4.10, 4.11, 4.12 and 4.13. The user preference weights have been varied for the two cases (A and B) and a series of corresponding designs have been generated. The results contained in Tables 4.10 and 4.12 present the absolute costs ($) and multi-criteria evaluation scores (for single-line diagram and equipment) characterizing the best and the worst design alternatives. In addition, Tables 4.11 and 4.13 contain information regarding the busbar arrangements and the types of major substation equipment selected. Thus, it can be observed that when cost is selected as a predominant criterion, the less expensive arrangements (breaker-and-half and double buses without sectionalizers in case A as shown in Table 4.11, row A-2, and breaker-and-a-half and single-buses in case B as shown in Table 4.13, row A-2) are preferred. As for the substation equipment, less costly circuit breakers (SF6 dead tank compared to live tank, row A-2, Tables 4.11 and 4.13) have been selected, as well as the ACSR conductor busbars and three-phase transformer units where feasible.

On the other hand, when the reliability criterion is stressed, the double busbar arrangements with sectionalizers have been selected, the SF6 live tank breakers were implemented and tubular lower busbars and single-phase transformer units were preferred. These alternatives consequently entail higher absolute costs as observed from Table 4.10 (row A-1). Finally, a set of designs has been generated emphasizing the impact on the environment criterion. It can be observed that in the cases (A-4 and A-8) where the impact on the environment significantly dominates other criteria, air blast circuit breakers were the preferred options since they have the least potential impact on the environment (no danger of a possible leak of SF6 gas). However, the absolute cost of these alternatives is rather high due to the selection of double busbars with sectionalizers based on other considerations such as the weights assigned to the reliability and operational flexibility.

In conclusion, the reliability and cost criteria has the greatest impact on the single-line diagram selection. As far as the operational flexibility is concerned, it has some bearing on the choice of busbar arrangements and types of electrical apparatus. As for the impact on the environment, it mostly influences the selection of substation electrical equipment, circuit-breakers in particular.

Based on the experience obtained running SIDE and comparing it with existing designs, it is possible to conclude that the user preference with respect to the four basic criteria in power system planning commonly adopted by substation designers could be as follows:

1. Reliability	40%
2. Cost	35%
3. Operational flexibility	15%
4. Impact on the Environment	10%

In other words, cost and reliability probably have dominated most existing substation designs.

Table 4.10: Multi-criteria sensitivity analysis - case A.

CASE	ABS.COST	COST_S	OPER_SLD	ENV_SLD	OPER_EQ	ENV_EQ	TOTAL_S
EVALUATION SCORES - BEST ALTERNATIVES							
A - 1*	79029600 $	10	/	/	/	/	10
A - 2	62220300 $	10	/	/	/	/	10
A - 3	76023600 $	/	10	/	8.6	/	10
A - 4	76011600 $	/	/	2.9	/	10	10
A - 5*	70347744 $	8.8	10	10	8.6	8.8	10
A - 6	62220300 $	10	9.5	7.9	6.4	6.3	10
A - 7	70355240 $	8.8	10	10	8.6	8.8	10
A - 8	76011060 $	8.2	8.4	2.9	10	10	10
EVALUATION SCORES - WORST ALTERNATIVES							
A - 1*	73029600 $	6.4	/	/	/	/	6.4
A - 2	79029600 $	7.9	/	/	/	/	7.9
A - 3	70917000 $	/	8.4	/	5.7	/	7.9
A - 4	62220300 $	/	/	7.9	/	6.4	8.7
A - 5	70909040 $	8.8	8.4	2.9	5.7	5.7	8.4
A - 6	79029600 $	7.9	9.5	6.4	8.0	8.2	9.1
A - 7	70915040 $	8.8	8.4	2.9	5.7	5.7	8.1
A - 8	70905600 $	8.8	10	10	5.7	5.7	9.6

ABS.COST - TOTAL COST IN $
COST_S - EVALUATION SCORES WITH RESPECT TO COST
OPER_SLD - SLD SCORES WITH RESPECT TO OPERATION FLEXIBILITY
ENVIR_SLD - SLD SCORES WITH RESPECT TO ENVIRONMENTAL IMPACT
OPER_EQ - EQUIPMENT SCORES WITH RESPECT TO OPERATIONAL FLEXIBILITY
ENV_EQ - EQUIPMENT SCORES WITH RESPECT TO ENVIRONMENTAL IMPACT
TOTAL_S - EQUIVALENT SCORES OF FINAL DESIGN

Table 4.11: Multi-criteria sensitivity analysis - impact on the equipment selection - case A.

CASE	HV BUS	LV BUS	BREAKER (HV)	BUS COND. (LV)	TRANSFORMER
EVALUATION SCORES - BEST ALTERNATIVES					
A-1	DOUBLE_BS	DOUBLE_BS	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
A-2	BREAK-HALF	DOUBLE-B	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
A-3	DOUBLE_BS	DOUBLE_BS	SF6-LIVE-TANK	TUBE-CU	OIL-1PH-AUTO
A-4	DOUBLE_BS	DOUBLE_BS	AIR-DEAD-TANK	CABLE-AL	OIL-1PH-AUTO
A-5	BREAK-HALF	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
A-6	BREAK-HALF	DOUBLE_B	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
A-7	BREAK-HALF	DOUBLE_BS	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
A-8	DOUBLE_BS	DOUBLE_BS	SF6-LIVE-TANK	CABLE-AL	OIL-1PH-AUTO
EVALUATION SCORES - WORST ALTERNATIVES					
A-1	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	CABLE-AL	OIL-1PH-AUTO
A-2	DOUBLE_B	DOUBLE_BS	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
A-3	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	TUBE-CU	OIL-1PH-AUTO
A-4	BREAK-HALF	DOUBLE_B	AIR-DEAD-TANK	CABLE-AL	OIL-1PH-AUTO
A-5	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
A-6	DOUBLE_B	DOUBLE_BS	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
A-7	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
A-8	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	CABLE-AL	OIL-1PH-AUTO

DOUBLE_B	-	DOUBLE BUSBARS WITHOUT SECTIONALIZERS
DOUBLE_BS	-	DOUBLE BUSBARS WITH SECTIONALIZERS
BREAK-HALF	-	BREAKER-AND-A-HALF ARRANGEMENT
SF6-LIVE-TANK	-	CIRCUIT BREAKER TYPE (SF6 MEDIUM, LIVE TANK CONSTRUCTION)
SF6-DEAD-TANK	-	CIRCUIT BREAKER TYPE (SF6 MEDIUM, DEAD TANK CONSTRUCTION)
AIR-DEAD-TANK	-	CIRCUIT BREAKER TYPE (AIR MEDIUM, DEAD TANK CONSTRUCTION)
TUBE-AL	-	TUBULAR ALUMINUM BUS CONDUCTORS
TUBE-CU	-	COPPER TUBULAR BUS CONDUCTORS
CABLE-AL	-	STRANDED WIRE CONDUCTOR ACSR
OIL-1PH-AUTO	-	OIL, SINGLE-PHASE AUTO TRANSFORMER
OIL-3PH-AUTO	-	OIL, 3 PHASE AUTO TRANSFORMER

Table 4.12: Multi-criteria sensitivity analysis - case B.

CASE	COST	COST_S	OPER_SLD	ENV_SLD	OPER_EQ	ENV_EQ	TOTAL_S
EVALUATION SCORES - BEST ALTERNATIVES							
B - 1	58346640	10	-	-	-	-	10
B - 2	55448900	10	-	-	-	-	10
B - 3	76023600	8.2	9.5	-	10	-	10
B - 4	62220300	-	9.5	6.9	-	10	10
B - 5	70347740	8.8	10	10	8.6	8.8	10
B - 6	62220300	8.9	9.5	8.1	10	10	10
B - 7	70357800	8.8	9.5	8.8	10	10	10
B - 8	62220320	8.9	9.5	8.1	10	10	10
EVALUATION SCORES - WORST ALTERNATIVES							
B - 1	63980000	6.1	-	-	-	-	6.1
B - 2	70217600	7.9	-	-	-	-	7.9
B - 3	62223380	10	9.5	-	6.4	-	8.9
B - 4	63262200	-	-	10	-	5.9	7.8
B - 5	67891040	9.2	8.9	6.9	7.9	7.5	9.4
B - 6	63446200	8.7	9.5	8.8	5.7	5.5	9.0
B - 7	71101600	8.8	9.5	8.1	6.9	6.7	8.8
B - 8	63446200	8.7	9.5	8.8	7.9	5.5	7.8

ABS.COST - TOTAL COST IN $
COST_S - EVALUATION SCORES WITH RESPECT TO COST
OPER_SLD - SLD SCORES WITH RESPECT TO OPERATION FLEXIBILITY
ENVIR_SLD - SLD SCORES WITH RESPECT TO ENVIRONMENTAL IMPACT
OPER_EQ - EQUIPMENT SCORES WITH RESPECT TO OPERATIONAL FLEXIBILITY
ENV_EQ - EQUIPMENT SCORES WITH RESPECT TO ENVIRONMENTAL IMPACT
TOTAL_S - EQUIVALENT SCORES OF FINAL DESIGN

Table 4.13: Multi-criteria sensitivity analysis - impact on the equipment selection - case B.

CASE	HV BUS	LV BUS	BREAKER HV	BUS COND. LV	TRANSFORMER
BUSBAR ARRANGEMENTS AND EQUIPMENT TYPES - BEST ALTERNATIVES					
B - 1	DOUBLE_BS	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
B - 2	BREAK-HALF	SINGLE_BS	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
B - 3	DOUBLE_BS	DOUBLE_BS	SF6-LIVE-TANK	TUBE-CU	OIL-1PH-AUTO
B - 4	BREAK-HALF	DOUBLE_B	AIR-DEAD-TANK	CABLE-AL	OIL-1PH-AUTO
B - 5	BREAK-HALF	DOUBLE_BS	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
B - 6	BREAK-HALF	DOUBLE_B	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
B - 7	BREAK-HALF	DOUBLE_BS	SF6-LIVE-TANK	TUBE-CU	OIL-1PH-AUTO
B - 8	BREAK-HALF	DOUBLE-B	SF6-LIVE-TANK	CABLE-AL	OIL-1PH-AUTO
BUSBAR ARRANGEMENTS AND EQUIPMENT TYPES - WORST ALTERNATIVES					
B - 1	BREAK-HALF	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
B - 2	DOUBLE_B	DOUBLE_B	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
B - 3	BREAK-HALF	DOUBLE_B	SF6-LIVE-TANK	TUBE_CU	OIL-1PH-AUTO
B - 4	DOUBLE_B	SINGLE_BS	AIR-DEAD-TANK	CABLE-AL	OIL-1PH-AUTO
B - 5	DOUBLE_BS	DOUBLE_B	SF6-LIVE-TANK	TUBE-AL	OIL-1PH-AUTO
B - 6	DOUBLE_B	SINGLE_BS	SF6-DEAD-TANK	CABLE-AL	OIL-3PH-AUTO
B - 7	DOUBLE_B	DOUBLE_B	SF6-LIVE-TANK	TUBE-CU	OIL-1PH-AUTO
B - 8	DOUBLE_B	SINGLE_BS	SF6-LIVE-TANK	CABLE_AL	OIL-1PH-AUTO

DOUBLE_B	-	DOUBLE BUSBARS WITHOUT SECTIONALIZERS
DOUBLE_BS	-	DOUBLE BUSBARS WITH SECTIONALIZERS
BREAK-HALF	-	BREAKER-AND-A-HALF ARRANGEMENT
SINGLE_BS	-	SINGLE BUSBAR ARRANGEMENT
SF6-LIVE-TANK	-	CIRCUIT BREAKER TYPE (SF6 MEDIUM, LIVE TANK CONSTRUCTION)
SF6-DEAD-TANK	-	CIRCUIT BREAKER TYPE (SF6 MEDIUM, DEAD TANK CONSTRUCTION)
AIR-DEAD-TANK	-	CIRCUIT BREAKER TYPE (AIR MEDIUM, DEAD TANK CONSTRUCTION)
TUBE-AL	-	TUBULAR ALUMINUM BUS CONDUCTORS
TUBE-CU	-	COPPER TUBULAR BUS CONDUCTORS
CABLE-AL	-	STRANDED WIRE CONDUCTOR ACSR
OIL-1PH-AUTO	-	OIL, SINGLE-PHASE AUTO TRANSFORMER
OIL-3PH-AUTO	-	OIL, 3 PHASE AUTO TRANSFORMER

4.4 Further Validation of SIDE

In order to further validate the capability of SIDE to generate reasonable substation designs, the software was run for the design specifications corresponding to the original Hydro Quebec substation at Manicouagan. This is a transformer substation having two voltage levels (735 and 315 kV), five high-voltage lines and nine 315 kVoutgoing circuits. The power rating is 1500 MVA. The short-circuit and overvoltage parameters are the same as in the cases A and B analyzed in the previous subsections. The deterministic reliability criterion considers two credible events, namely, *breaker-out-of-service + line fault* and *line fault + breaker-fails-to-trip*. As for the undesirable consequences, a fairly severe reliability criterion is chosen, that is, the outage of any two substation components is not allowed. The reliability criterion is also heavily stressed by assigning to it a user preference weight of 100% while placing zero weight on the other three design criteria.

Tables 4.14 and 4.15 present some of the more significant output results generated by SIDE for this study. Table 4.14 contains the general design data as well as the selected busbar arrangements at both voltage levels for each design alternative. Note that one of the generated alternatives has the identical busbar arrangements at both voltage levels as the existing Manicouagan substation (ALTERNATIVE-1). More information related to this design alternative is provided in Figure 4.2 which displays its complete single-line-diagram. It can be observed in this figure that other substation composite parts selected by SIDE such as line terminations and transformer groups are also identical to those implemented in the Manicouagan substation [SLD93]. Apart from the single-line-diagram, the results obtained from simulations also support the validation of SIDE. Thus, as shown in Table 4.15, the number and size of transformer units selected corresponds almost exactly to those employed in Manicouagan (4 units in both cases, 500 MVA as compared to Manicouagan's 510 MVA).

Table 4.14: General design information - SIDE's design corresponding to Manicouagan specifications.

DESIGN TITLE:	MANICOUAGAN STUDY	
TYPE OF SUBSTATION:	TRANSFORMER - RURAL	
POWER RATING:	1500 MVA	
VOLTAGE LEVEL:	HIGH VOLTAGE	LOW VOLTAGE
VOLTAGES:	735 kV	315 kV
NUMBER OF CIRCUITS:	6	9
LOCATION:	OUTDOORS	OUTDOORS
BUSBAR ARRANGEMENTS		
ALTERNATIVE - 1	DOUBLE BUSES WITH SECT.	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 2	BREAKER-AND-A-HALF	DOUBLE BUSES WITH SECT.
ALTERNATIVE - 3	DOUBLE BUSES WITH SECT.	DOUBLE BUSES
ALTERNATIVE - 4	BREAKER-AND-A-HALF	DOUBLE BUSES

Table 4.15: Simulation results - SIDE's design corresponding to Manicouagan specifications..

TRANSFORMER ANALYSIS		SHORT-CIRCUIT CALCULATIONS	
NUMBER OF UNITS:	4	THREE-PHASE FAULT - HV:	30 kA
UNITS SIZE:	500 MVA	THREE-PHASE PEAK - HV :	51 kA
UNIT IMPEDANCE:	12 %	THREE-PHASE FAULT - LV :	29 kA
TAP CHANGER:	2 x 2.5 %, -2 x 2.5 %	THREE-PHASE PEAK - LV :	43 kA
INSULATION COORDINATION		**COST EVALUATION**	
PHASE-TO-GROUND - 735 kV		ALTER.	COST ($)
MAXIMUM VOLTAGE:	765 kV	ALT-1	71553200
LIGHTNING WITHS. VOLTAGE:	1950 kV	ALT-2	63429200
SWITCHING WITHSTAND VOLTAGE:	1550 kV	ALT-3	60218300
		ALT-3	52094300
PHASE-TO-GROUND - 315 kV			
MAXIMUM VOLTAGE:	330 kV		
LIGHTNING WITHSTAND VOLTAGE:	1175 kV		
SWITCHING WITHSTAND VOLTAGE:	950 kV		
60 HZ WITHSTAND VOLTAGE:	-		

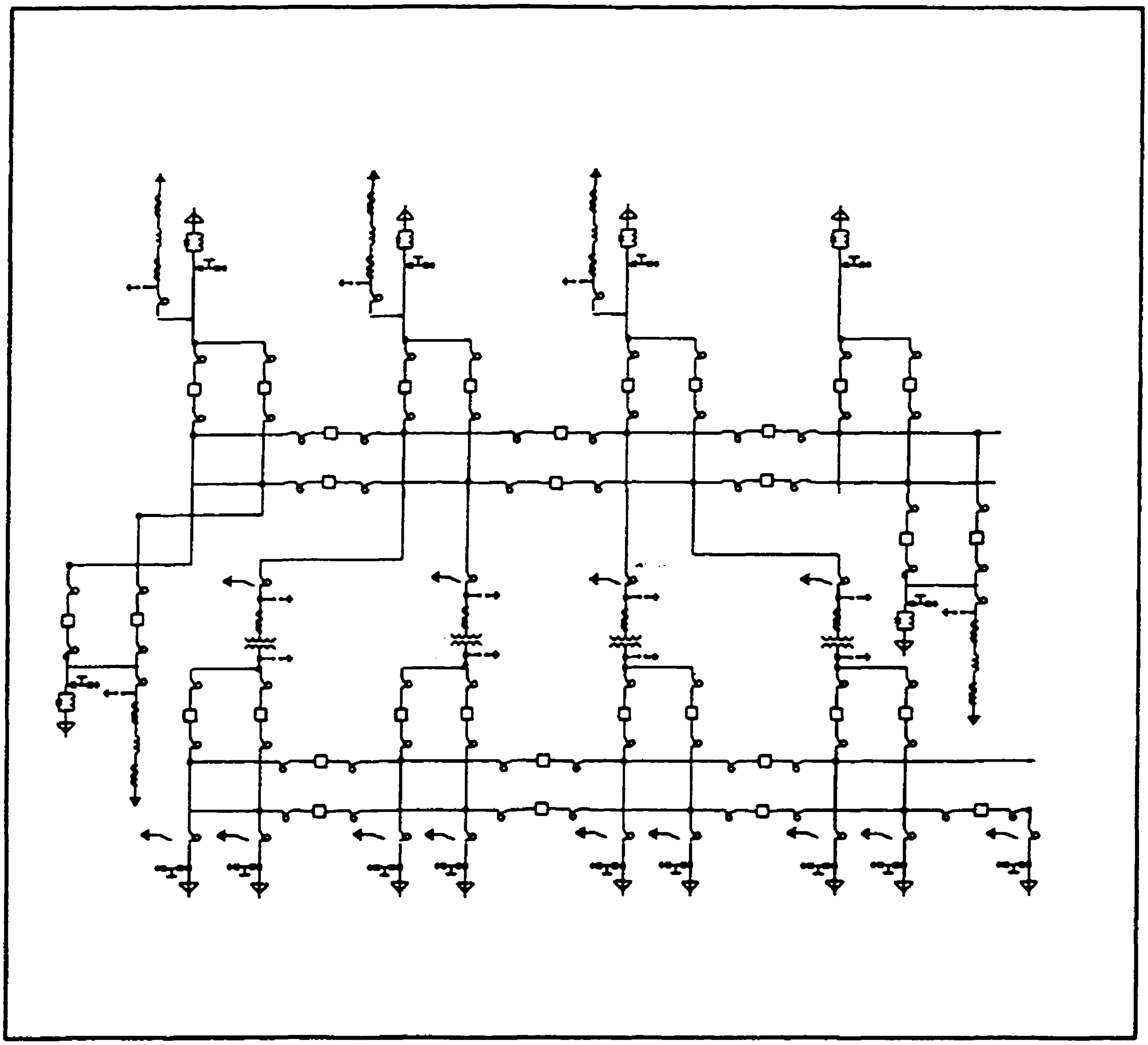

Figure 4.2: Single-line-diagram - Manicouoagan study.

5. CONCLUSIONS

Planning and design activities in electric power systems strongly depend on a broad knowledge base typically dispersed over numerous sources. Some aspects of this knowledge are documented in reports, textbooks, journal articles, design manuals and computer databases but much of the available knowledge is in the minds of human experts spread within electric power utilities, manufacturers and consulting firms. Furthermore, much of this planning and design knowledge is empirical, derived from actual experience rather than from well-defined numerical procedures based on the laws of nature. Finally, a long-term trend of increasing retirements of experienced planning engineers who leave without passing on their expertise to other experts contributes significantly to the erosion of planning and design knowledge in power systems.

Motivated in part by the above trends, an intelligent model for power system planning and design was proposed and developed in this thesis. The aim of this development was first to identify a wide body of planning and design knowledge and then to gather it and structure it into one easily accessible source for purposes of preservation, consolidation and training. Following this direction, the main planning activities of complete power systems and of specific important subsystems have been identified and delineated. The resulting proposed integrated planning model, PSIDE (power system intelligent design and planning environment), is structured in a manner analogous to the organization of the planning department in a typical power utility. Thus, the activities performed at the highest level are supported by the *Director of System Planning* module, which, based on the inputs provided and the planning objectives defined, assigns appropriate responsibilities to its subordinate modules, namely, the *Generation Manager* and the *Transmission Manager* modules. Similarly, following a well-established planning hierarchy, these modules access other major and supporting expert systems (point-to-point transmission, substation design, expansion planning, demand-side management, insulation coordination) as well as numerous available simulation tools (short-circuit analysis, reliability evaluation, load flow and stability).

A general methodology based on object-oriented programming for the realization of the intelligent knowledge-based planning tool, PSIDE, has been proposed and developed in this thesis. The object-oriented approach is highly justified for modelling design and planning knowledge in electric power systems because of the complex nature of such systems and the natural way in which they can be subdivided into classes of objects. Viewed from the synthesis point-of-view, object-oriented programming is very well suited for creating (designing) more complex objects by combining sets of simpler subobjects following a collection of instructions (methods) imbedded and distributed in the knowledge base of the constituent objects themselves. As far as planning and design activities are concerned, it was observed that most of these tasks are generally carried out in a sequence of well-established steps where the design knowledge associated with each step is independently processed. Furthermore, it was shown that two basic knowledge categories can be identified, namely, *top-level knowledge* which is processed when global planning decisions are being made (e.g. selection of system configuration, single-line diagrams) and *low-level knowledge* which is used when more specific local tasks are to be performed (e.g. selection of power system components). Based on such knowledge distribution, a general object-oriented model was developed for PSIDE. This model consists of an equipment database where different types of electrical apparatus are stored, several class hierarchies of *system composite parts* modelling the more common configurations and arrangements, a class of *simulation* tools where the commonly used numerical procedures are preserved and a *design-session* class which models the resulting object and contains a set of final design alternatives as well as all other information pertinent to the design session.

The development of this intelligent integrated model to support power system planning and design tasks was motivated by the increased complexity of power systems and by the erosion of experienced personnel in this field. However, it is important to clarify that the intended purpose of such a knowledge-based tool is not to create powerful computer programs with sufficient intelligence and knowledge that they can fully perform as human engineers. Rather the main reason behind this research was, actually, to build a system which will assist experts in the design process and which can be used for educational purposes by providing a powerful training facility for less experienced engineers.

In order to support the general design tool, PSIDE, object-oriented models of some typical power system design tasks such as point-to-point transmission design, insulation coordination and protection design have been proposed as well and are described in this thesis.

As one of the major contributions of this research, an object-oriented tool for *substation design* (SIDE) was fully developed and is discussed in detail in the second part of this thesis.

The first step in this development of SIDE was to analyze the general structure of substations and to establish an object-oriented model. As a result of this analysis, a typical substation is represented by five main composite parts, namely, high-voltage line terminations, high-voltage substation buses, transformer and compensation groups, low-voltage buses and low-voltage line terminations. These main parts are further subdivided into more basic electrical equipment. SIDE takes advantage of this substation composition to systematically structure the knowledge associated with substation design in an object-oriented manner. Thus, the whole substation is modeled as an object containing five objects representing the five main composite parts which in turn contain numerous other objects modelling the substation basic electrical equipment. In addition to the object-oriented representation of the substation, several class hierarchies have been defined modelling the various possible arrangements of substation composite groups.

The second step in the development of SIDE was to identify, collect and structure substation technical design knowledge. It was shown that this knowledge can be mainly classified into two basic categories: heuristic knowledge based on human expertise (mostly related to top-level global knowledge and global activities such as the selection of a single-line diagram) and the knowledge associated with the use of various simulation tools which support the design process such as short-circuit analysis, insulation coordination, transformer preliminary analysis and reactive power management. Since substation design, like most other power system design activities, is performed in a sequence of well- established design steps, the concept of knowledge distribution was extensively employed when structuring the SIDE domain knowledge. Thus, knowledge was compartmentalized and encapsulated in system classes according to the tasks which are performed to instantiate these classes. The important benefit which stems from such a knowledge distribution is that no sophisticated inference engine is needed to govern the design process since the knowledge involved in the instantiation of the substation objects is independently processed. The order of instantiation of all substation objects is determined in the above-mentioned sequence of predetermined design steps, thus eliminating possible conflicting situations.

A vital component of any power system planning and design tasks is the definition and selection of design criteria. Four basic design criteria are considered in the course of this research, namely, cost, reliability, operational flexibility and the impact on the environment. The variable user-preference weights assigned to these criteria as well as the fixed relative scores assigned to the various design components with respect to the same criteria have a major impact on the final design. These weights and scores are considered as being part of the top-level knowledge processing when the substation single-line diagram is being selected. They also influence the selection of some important substation equipment such as transformers, circuit-breakers, busbar conductors and reactive-power compensation equipment. User-preference weights and fixed relative scores serve to quantify the performance of the above mentioned substation components as well as the performance of the complete design enabling SIDE to recommend the best among all feasible design alternatives.

Apart from these quantitative measures, there exists a set of criteria which could be classified as feasibility constraints. In power system planning and design, these criteria constraints impose insulation levels, short-circuit capacities and deterministic reliability requirements which each feasible design must satisfy. Such constraints are usually specified as a part of the input design specifications and also play a key role in the final design.

The last chapter of this thesis presents applications of SIDE that demonstrate the validity and the reasonableness of its designs. This chapter also demonstrates the ability of the tool developed to design a large number of candidate designs in a very short period of time, to carry out sensitivity analyses and to reproduce designs which are very similar to existing substations. All of these results tend to suggest that the tool is capable of emulating human expertise.

In particular, two design cases were extensively tested differing mostly in the specified deterministic reliability criterion. In addition to these two basic cases, a set of 16 additional cases was generated by varying the levels of the user-preference weights in order to perform a sensitivity analysis on the relative importance assigned to the different design criteria. The resulting design alternatives provided by SIDE were found highly consistent with existing designs and realistic as judged by experienced human experts. The major design points which have been evaluated by these tests were the substation single-line diagrams and the electrical equipment specification (tender document). The results of the sensitivity analysis were used to evaluate the impact of a change in criteria preferences on the final design, particularly the single-line diagram, the substation equipment as well as the total multi-criteria evaluation scores of the complete design.

In addition to the above-mentioned testing, the practical validation of SIDE was accomplished through the design of one of the substations of Hydro Quebec, namely, "Manicouagan". Given the design specifications closely corresponding to the original Manicouagan Substation, SIDE generated a series of design alternatives among which was the one having the same single-line diagram configuration as the Manicouagan substation. As for the other design characteristics such as electrical equipment, it can be affirmed that SIDE provided a design having equipment characteristics almost identical to those of Manicouagan Substation.

Future objectives are mostly related to the full development of PSIDE's knowledge-based and expert system modules which are conceptually discussed in this thesis and of which SIDE is a significant component. This development includes activities such as knowledge acquisition, object-oriented modelling and the implementation using C++ programming language. Since each of these activities represents an extensive task, the final integration of these expert system modules into PSIDE is seen as a long-term objective and one which will make a siginficant contribution to the planning and design of electric power systems.

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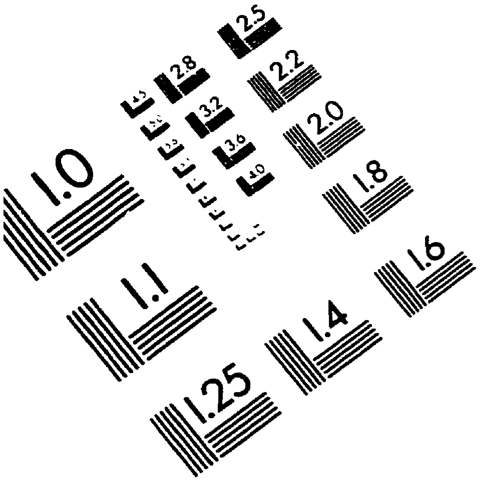
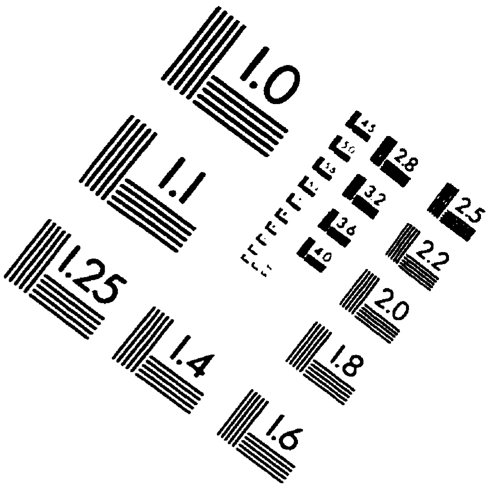
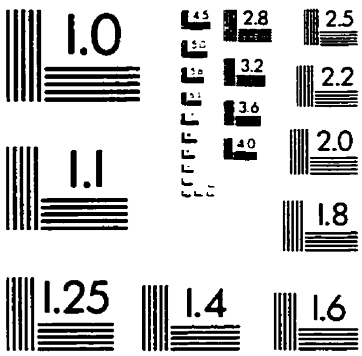
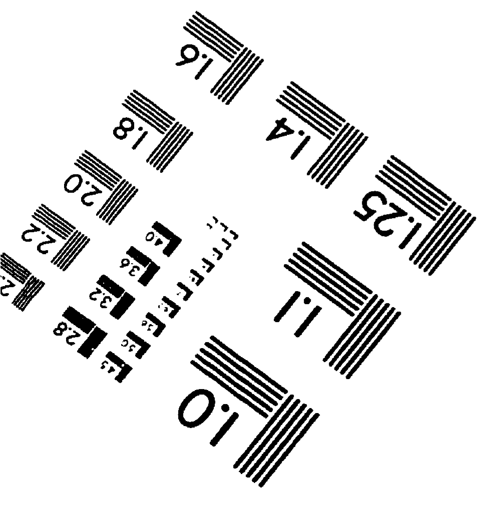
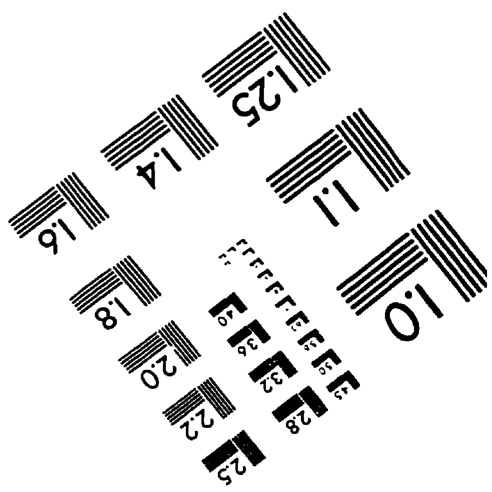
IMAGE EVALUATION TEST TARGET (QA-3)

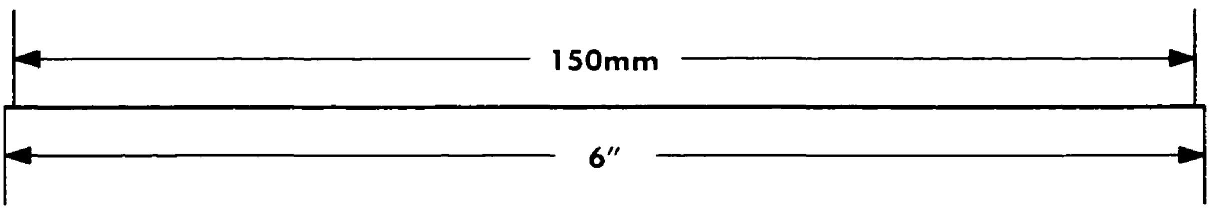












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