AN EXPERT SYSTEM FOR PROTECTION SYSTEM DESIGN OF INTERCONNECTED ELECTRICAL DISTRIBUTION CIRCUITS

by

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(ABSTRACT)

As necessity for improvement in system operation demands the implementation of distribution automation, design of the protection system becomes more involved. Several goals of distribution automation -- improved customer reliability, reduced systems losses, and balancing of substation loading -- are dependent on the ability to perform automatic circuit reconfigurations. A prerequisite for implementing automatic circuit reconfiguration is that the protection system design must operate properly for all configurations.

An integrated expert system for the protection system design of interconnected distribution circuits has been developed using the DANE engineering workstation. The expert system incorporates the basic requirements and guidelines as specified by IEEE for protection system design. The expert system uses a relational database management system, integrates system data, and provides a graphical user interface. The expert system incorporates both procedural and declarative, or query, operating modes. Rules dealing with the coordination, placement and selection of protective devices are presented that are used to dynamically, incorporate expert knowledge into the knowledge base. The protection system designer controls which rules are implemented in the design.

An example protection system design is presented using the integrated expert system developed for DANE. The example problem consists of three interconnected distribution circuits. Dynamic knowledge, created by the expert system from the rules and system data, is used in the design. System data is presented pertaining to the circuits along with the created dynamic knowledge. The implemented rules dealing with the coordination, placement and selection of protective devices are presented, along with all associated parameter values. The final protection system design and results are presented in a research report.

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Words alone will never be able to express the thanks I owe my parents. Their endless support and love have, and will always, be an inspiration to me. In this chaotic world in which we live, I am reminded, almost daily, that I am truly blessed. I am thankful that God provided me with such wonderful parents.

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CHAPTER 1

Introduction

Electricity is supplied to a variety of customers via a complex network. The majority of electricity is produced at large generation plants by various methods with the most common methods being fossil, nuclear and hydro. These generation plants are centrally located along major waterways and fuel sources. Electricity must be supplied from these generation sites to customers by way of the electric network. The overall electric network is generally viewed as two distinct operational systems.

A portion of the network transfers electricity from the generation sites to substations that are dispersed locations in the network. This part of the electric network is commonly referred to as the transmission operation level. The transmission level is characterized by the two features of high voltage levels, from 135 KV up to 765 KV, and meshed, or looped, circuits. The high voltage levels tend to reduce systems losses, and the meshed circuits facilitate multiple paths to supply loading at substations.

From the dispersed substations the electrical system supplies electricity to the customers. This portion of the network is commonly known as the distribution operation level. Two distinct features of a distribution system are lower voltage levels, usually from 135 KV down to 4 KV, and radial circuits. Conductor sizes and safety concerns mandate lower voltages at the distribution level. Distribution circuits are radial in nature which implies no loops are present in the system. During operation only a single source at the substation supplies all customers attached to a radial circuit. This radial structure of the circuits is primarily due to the costs and load dynamics. The construction costs for radial circuits are much cheaper than those for meshed circuits.

The reliability of supply to a customer is of major importance, since the industry is a service oriented sector. Reliability is a qualitative measure of how efficient the utility is in maintaining a constant power supplied to its customers. The electric power system network in United States has been rated the most reliable worldwide [1].

The reliability of the power industry to supply electricity is due in large part to the performance at the distribution level. Most end-use customers are supplied through local distribution systems or utilities. These utilities are responsibility for maintaining a reliable supply of electricity to its customers over its distribution circuits.

The reliability of any electrical power system is dependent largely on the proper operation of its overcurrent protection system [2]. The proper operation of the protection system is dependent upon its overall design [3]. For example, if a fuse blew every time a temporary fault occurred on a line then customers would experience longer outages, and reliability would be worse due to an improperly designed protection system. The planning process involved in the protection system design ultimately determines how effectively the protection system design responds and operates during periods of overcurrents on the system.

The designers of overcurrent protection systems for electrical distribution circuits confront numerous problems. These problems must be addressed if the design is to properly function. Reference 4 notes this design process "is part science and part art." Numerous decisions and tradeoffs exist in the process which leads to the artwork in the design. For an electrical circuit, multiple protection system design schemes will exist that perform the intended function.

The design of the protection system involves both the collection and analysis of various data about the distribution circuits. Data from fault analysis, power flow, and protective devices along with the circuit configurations of the distribution system must all be collectively used in this design. Manuals on standard practices and approaches have been written by both organizations and manufacturers that address the design process [1,5,6,7]. A wide variety of workshops are conducted to assist and educate the protection system design engineer. These workshops provide background notes, standard practices among utilities, and typical device operational data to use as reference data by the engineer [4].

It is not uncommon, particularly among the smaller utilities, for a single person to be solely responsible for designing protection systems. This type of situation produces human experts in protection system design purely from their experience gained over the years. The major disadvantage of this arrangement is when the human expert retires or leaves the company.

The function of a protection system is to protect both the general public and the electrical system equipment [8]. When faults occur on the electrical system, the protection system must be able to take corrective actions. This prevents both damages to the electrical equipment and human exposure to dangerous conditions. If overcurrent system faults are not cleared, tremendous damage can be inflicted on the electrical equipment components of the circuit, or worse human fatalities may result from contact with faulted circuit components, such as fallen, energized conductors.

The majority of fault conditions are characterized by current flows on the circuit that are significantly above the normal current flow due to system loading. Fault conditions are caused by a wide array of factors. The vast majority of faults are temporary in nature such as when high winds cause bare conductors to come into contact momentarily [8]. This creates a transient fault condition that will correct itself when the conductors separate. However, a fault current is generated from the temporary short circuit between the bare conductors which must be corrected by the protection system.

During fault conditions, excessive current may flow through several protective devices in the system. Upon sensing the overcurrent the affected devices will operate based on their operating characteristics. Initially, the protection system should treat the fault as temporary in nature. Therefore, the protection system should perform some automatic circuit reclosing in an attempt to clear the fault.

If the fault persists and the automatic circuit reclosing operations do not clear the fault, the situation is handled as a permanent fault. At this point, the closest protective device to the fault location should operate to clear the fault before any other affected devices perform permanent fault clearing operations. The closest protective device is defined here as that protective device that is encountered first when going from the fault location back along the circuit towards the substation.

A protection system is composed of strategically located protective devices throughout the system of distribution circuits. The basic protective devices consist of breakers with attached relays, automatic reclosers, sectionalizers, and fuses. Relay controlled breakers and reclosers have automatic circuit reclosing capabilities. At the distribution substation, either a breaker or recloser is used as the main circuit protection. Reclosers, sectionalizers, and fuses are primarily utilized for protection out on the circuit. The basic intent of the protection design scheme is for breaker controlled relays and reclosers to provide total system coverage to clear all temporary faults, and only have fuses operate for permanent faults [1].

1.1 General Design Process

A general description is given for the steps in the design process. The fault currents must be known for each component on the circuit. This mandates that some type of fault analysis, or short circuit calculations, must be performed for the circuit under study. The fault analysis considers various fault types such as 3-phase bolted, 3-phase-to-ground, 2-phase bolted, and 1-phase-to-ground faults. A set of maximum and minimum fault currents is calculated that each circuit component could experience when considering all of these different fault types.

Using the calculated fault currents, the designer must decide at which circuit locations to place protective devices. The placement of devices is based on such considerations as the type of devices available, circuit length, cost, and customer loading. Some common rules of thumb are used in the placement of devices. The placement of protective devices at the start of all lateral line sections and relay controlled breakers or reclosers at the substation are both examples of common rules of thumb.

After determining placement of devices, the final step is the selection of coordinated devices. Any device selected must meet required circuit specifications, such as device voltage, load flow current, and fault current interrupting ratings. Simultaneously, any selected device must be coordinated with all other relevant devices. Coordination implies that only the closest upstream protective device should operate during any permanent fault condition.

The coordination of the selected protective devices is typically performed using data from Time Current Characteristic curves associated with the devices. This can be a laborious, time-consuming process as numerous devices are checked against each other [9]. Some manufacturers supply tables showing device coordination among devices that they produce to aid in this process. These tables give the device combinations and the range of fault currents over which they coordinate together.

Often more protective devices may have to be placed on the circuit to achieve coordination among devices. This addition of more protective devices may occur during the planning stages or in later years. Over time as circuits expand, an upgrade of existing protective devices will be necessary to maintain proper operation of the protection system due to load growth on the circuit.

Unexpected load growth accounts for as much as 50 percent of improper protection system operations [1]. This occurs because normal current flow to supply circuit loading increases to the point that it equals the minimum fault current levels calculated in the original design. Thus, the protection system mistakenly senses the new load current as an overcurrent fault and performs clearing operations on the circuit. At this point the protection system must be updated to handle the increased loading.

1.2 Factors Influencing Protection System Design

Utilities are implementing distribution automation features that among other things strive to reduce system losses, to balance loading among substations and to decrease peak loading conditions. The ability to perform reconfiguration of interconnected circuits in the distribution system has been shown to achieve some of these results [10]. For interconnected radial circuits the actual configuration of the system will affect the calculation of both fault currents and load flows. A protection system designed for solely one configuration of the distribution system becomes invalid when the system undergoes reconfiguration.

Customer reliability is improved when outaged customers are re-supplied by alternative routes [11]. Reliability can be improved if the utility is able to perform automatic reconfiguration of the distribution circuits following outages. However, a proper protection system design is a prerequisite for being able to perform reconfiguration.

Another recent trend of concern for local utilities is cogeneration. Cogeneration is broadly defined here as some industry that generates a surplus of electricity at its facility. This energy surplus may be continuous or only for certain periods of time. By law the utility must allow the cogeneration facility access to the distribution system to sell surplus power. The problem is what affect the cogeneration has during faults on the distribution system [12]. The cogeneration source contributes to the induced fault current on the system. The cogeneration source will amplify the magnitude of the fault current flowing by some factor.

1.3 High Impedance Faults

It should be stated at this stage that even the most rigorously developed protection system will, unfortunately, not provide absolute protection for every type of fault on the system. Human fatalities still occur from human contact with energized downed conductors. Under certain conditions when electrical conductors break and fall to the earth the impedance is such that the protection system is unable to detect the generated fault current. This phenomenon is commonly referred to as high impedance faults. Because of the high impedance, the induced fault current is significantly below the minimum fault detection level of the protection system. Numerous research projects have been conducted to develop strategies to overcome this problem, as evident from a recent IEEE tutorial [13]. The study of high impedance faults is beyond the scope of this research.

1.4 Scope of Dissertation

As necessity for improvement in system operation demands the implementation of distribution automation, design of the protection system becomes more involved. Several goals of distribution automation -- improved customer reliability, reduced systems losses, and balancing of substation loading -- are dependent on the ability to perform automatic circuit reconfigurations. A prerequisite for implementing automatic circuit reconfiguration is that the protection system design must operate properly for all configurations.

Before reconfiguration occurs on the system, the utility must be confident that the protection system is adequate for the new circuit configurations. If the protection system has been designed to function solely for a given configuration of the distribution system, the protection system design becomes invalid whenever the configuration is changed for the system. The implementation of circuit reconfiguration often causes the protection system to operate incorrectly during faults. Thus, for interconnected circuits, multiple fault analysis and power flow studies must be conducted that encompass all feasible configurations of the system.

For interconnected radial circuits utilizing reconfiguration, certain line sections, referred to as tie-lines, will experience bi-directional current flows. Fault analysis will need to produce two sets of maximum and minimum fault currents for each such tie-line component. One set of maximum and minimum fault currents will be for the forward direction of current flow on the tie-line. Forward current flow is defined here as the current flow direction on the tie-line during the normal configuration of the circuit. The second set of maximum and minimum fault currents will be when the current flow reverses from the normal flow direction on the tie-line.

The design of the protection system for automated electrical distribution systems is the backbone for both improved customer reliability and implementation of circuit reconfiguration. An IEEE Committee Report concerning the design of protection systems stresses the importance of an integrated approach to the solution [15]. Numerous software packages exist that perform fault analysis for distribution circuits. Other software packages have been developed for the computerized coordination of protective devices. However, the majority of the software makes the designer responsible for interfacing data that is produced by disjoint software algorithms. An example would be coordination software that calculates the range of currents over which two devices coordinate, but is unable to utilize the previously calculated circuit's fault currents in determining if the devices can be placed at locations on the circuit.

The research work of Maghdan in protection system design was for distribution system applications; Maghdan's work used a relational database system scheme for data integration [16]. However, Maghdan's work did not address the critical issues of circuit reconfigurations, or the impact of cogeneration during fault conditions on the distribution system.

The goal of this research is to develop a totally integrated computer-aided approach to protection system design for electrical distribution systems. The key elements in the new approach are as follows:

(1) All of the pertinent data are both generated and stored for interconnected radial distribution circuits utilizing reconfiguration.

(2) The issues of cogeneration sources in the system during faults are taken into account.

(3) The methods for modeling and managing the data associated with protective devices are addressed.

(4) The performance testing of the developmental expert system implementation on interconnected distribution circuits.

An overview is presented for the remaining chapters. Chapter 2 provides a review of common terminology in the area of protection system design. An example of a time current characteristic curve for a protective device is given to graphically illustrate some of the terminology. Additionally, tables of symbols and abbreviations are presented for later reference purposes.

Chapter 3 is a review of previous works in the area of protection systems. As the literature indicates, the area of protection system consists of many facets that includes protective devices, fault studies and calculations, coordination studies, and computer algorithms.

Chapter 4 pertains to the DANE workstation. The key components of the workstation are presented which are critical to protection system design. In particular, a discussion is presented concerning the Fault, Power Flow, and Circuit Configurations analysis functions.

Chapter 5 deals with both the modeling and the management of the data associated with protective devices. The relational model used for the protective devices is presented. The modeling techniques developed are presented and an example is given which demonstrates the data management realized when implementing the developed modeling techniques.

Chapter 6 deals with the overall design of the developmental expert system. A discussion about the expert system implementation is presented concerning the computer language platform. The topics of and relationships between dynamic data creation, static data, influencing rules, and rule processors are discussed concerning how each affects the knowledge bases.

Chapter 7 provides a design example circuit pertaining to three interconnected distribution circuits. This data was supplied by Arkansas Power and Light from its Hot Springs Division in Arkansas. The expert rules associated with the Coordination, Placement, and Selection Rule Processors are described, which were implemented in the design. The results from the expert system design study are presented for the interconnected circuits. The locations for which protective devices were selected are graphically shown in the examples. The dynamically created protection object data is given that is utilized by the Selection Rule Processor. Example SQL Select statements are given that were utilized by the Selection Rule Processor, and the protective device data is presented regarding the selected devices.

Chapter 8 gives the conclusions and recommendations concerning the developmental expert system. The contributions are presented regarding this research along with suggestions that could be undertaken in the future to improve the work.

CHAPTER 2

Background Terminology

Some basic terminology is commonly used concerning the overall performance and operation of radial distribution protection systems. Some of the terminology concerns the radial circuits. Terms such as downstream and upstream are used when referring to device locations on a circuit. This terminology is used to identify device locations relevant to the substation source. The relevance to the substation or voltage source is due to the design of radial circuits. In general, upstream implies that the location is toward the substation while downstream is toward the end of the circuit away from the substation.

Primary and backup terminology are related to protective devices and protection zones. Unlike transmission level power systems, the zones of protection are not clearly definable for distribution power systems. This is due mainly to the dynamics involved in the expansion of the distribution circuit to supply new customer loading. The protective zones at the distribution level are loosely defined by the placement of the protective devices on the circuits during the design process. This device placement is based on common practice from experience with a particular protective device type.

Devices provide protection coverage for specific zones, or regions, of the electrical distribution circuit. The device that protects a particular zone is known as the Primary protective device for that zone. The purpose of the Primary device is to protect all components in the zone against permanent and temporary faults, unless the Primary device is a fuse. For fuses all temporary faults should be handled by automatic circuit reclosing devices [4]. This prevents unnecessary circuit outages due to blown fuses for temporary faults.

When looking from the substation out into the distribution system, the Primary device will have at least one Backup protection device; unless the Primary device is located at the substation. One purpose of the Backup device is to provide protection should the Primary Device fail to operate for a fault. All Backup devices associated with a given Primary device must be selected such that they allow ample time for the Primary device to clear all faults within its specific zone of protection. Additionally, the Backup device must serve as the Primary device for its primary zone of coverage. Thus, a protective device must functionally serve as both a Primary and Backup device, unless it is the last protective device on a lateral. The last protective device on any lateral serves as only a Primary device.

The topics of Sensitivity and Selectivity define the ability of the protective devices to detect faults on the circuit and operate to clear the faults. The operation of a protective device in clearing permanent faults, for only those permanent faults within its primary protection zone, refers to its Selectivity. A device's Selectivity must be such that for all permanent faults within its protection zone the device operates to isolate the faulted zone. The Sensitivity of a device concerns its ability to sense and to operate as a Backup device for a fault when the Primary device has been given ample time to operate but fails to clear the fault. Thus, a particular device must have Selectivity in clearing all faults within its primary protection zone, yet not normally operate for faults in its backup protective zones. However, its Sensitivity as a Backup device must be such that should any Primary device fail to operate, then the Backup device must operate to clear any fault.

A key topic involved in protection system design deals with Coordination between devices. Device Coordination is achieved when only the Primary Device operates for faults in its zone of protection. Coordination between the Backup and Primary protective devices must be achieved by proper selection of devices. The device selection criteria are based on several factors. A primary factor in device selection is the anticipated levels of fault current at a given protective device location. Protective devices are manufactured such that at a given current the device operates within a specific time. Manufacturers typically supply what are commonly known as the Time Current Characteristic curves describing the operational characteristics of devices.

2.1 Device and Time Current Characteristics

Time Current Characteristic, or TCC, curves are used to describe the operational characteristics of protective devices. TCC curves show the relationship for time versus current of the protective device. Using the TCC curve the engineer can determine the time necessary for a device to start operating or totally clear a given value of fault current.

Relays are used to control the operation of circuit breakers. Current Transformers are the most widely used method of physically connecting the relays to the actual electrical circuit. Relays are built to sense low current levels, between 5 and 100 amperes, and as such require some type of transformer to step down the actual fault currents [14].

A variety of relay types such Inverse, Very Inverse and Differential relays are available from manufacturers. These different relay types describe the operational relationship of the TCC curve. If a given fault persists for enough time the relay will initiate breaker operation. The relay sends a signal to the breaker causing the breaker to perform the fault clearing operation.

A relay will have multiple Time Dial Settings associated with it. A single Time Dial Setting must be chosen for the relay. In general, the Time Dial Setting linearly scales the time axis on the TCC curve. Thus, as the relay's Time Dial Setting increases, the operational time required for the relay also increases to clear a given value of fault amperes.

The TCC curve for a fuse involves two separate curves. When dealing with fuses, the Melting / Pickup and Total Clearing curves are synonyms, for the lower and upper TCC curves, respectively. The lower curve specifies the time required for the fuse to detect a given value of current. This detection of overcurrent is more commonly referred to as the fuse's pickup. When the fuse pickups on the fault current, it begins to melt which causes damage to the fuse. Thus, the lower curve is often referred to as either the Melting or Pickup Curve. Using the TCC data, the time that a temporary fault is allowed to persist before any fuse damage occurs can be determined using the lower curve of the TCC. A typical fuse TCC curve is shown in Figure 2.1.

The upper curve, or Total Clearing curve, for the fuse specifies the total time required for the fuse to completely melt at a given value of current. Using the TCC data, a designer can determine the time necessary for the fuse to completely clear for a permanent fault. This is accomplished by taking the given fault current and using the Total Clearing curve of the TCC to determine the time required for the fuse to melt.

In conjunction with automatic reclosers, the terms Instantaneous / Fast Trip and Lockout / Delayed Trip curves are used for the lower and upper TCC curves, respectively. Additionally, the total number of operations on the lower and upper curves is encountered in the literature concerning automatic reclosers. The TCC curve for an automatic recloser also involves two separate curves. Reclosers have a family of operational curves from which two curves may be chosen for implementation. The utility has the option of setting which two curves to implement. The arrangement of the hardware wiring configuration, internal to the recloser, determines which two curves are utilized during fault operations. When the recloser performs a fault induced operation the recloser remains open for brief time intervals.

The lower curve, or Fast Trip, is used to perform fast, or Instantaneous, operations during faults. The lower curve is used to clear temporary faults. The upper curve, or Delayed Trip, provides a longer operation time period to clear persistent, or longer duration, temporary faults.

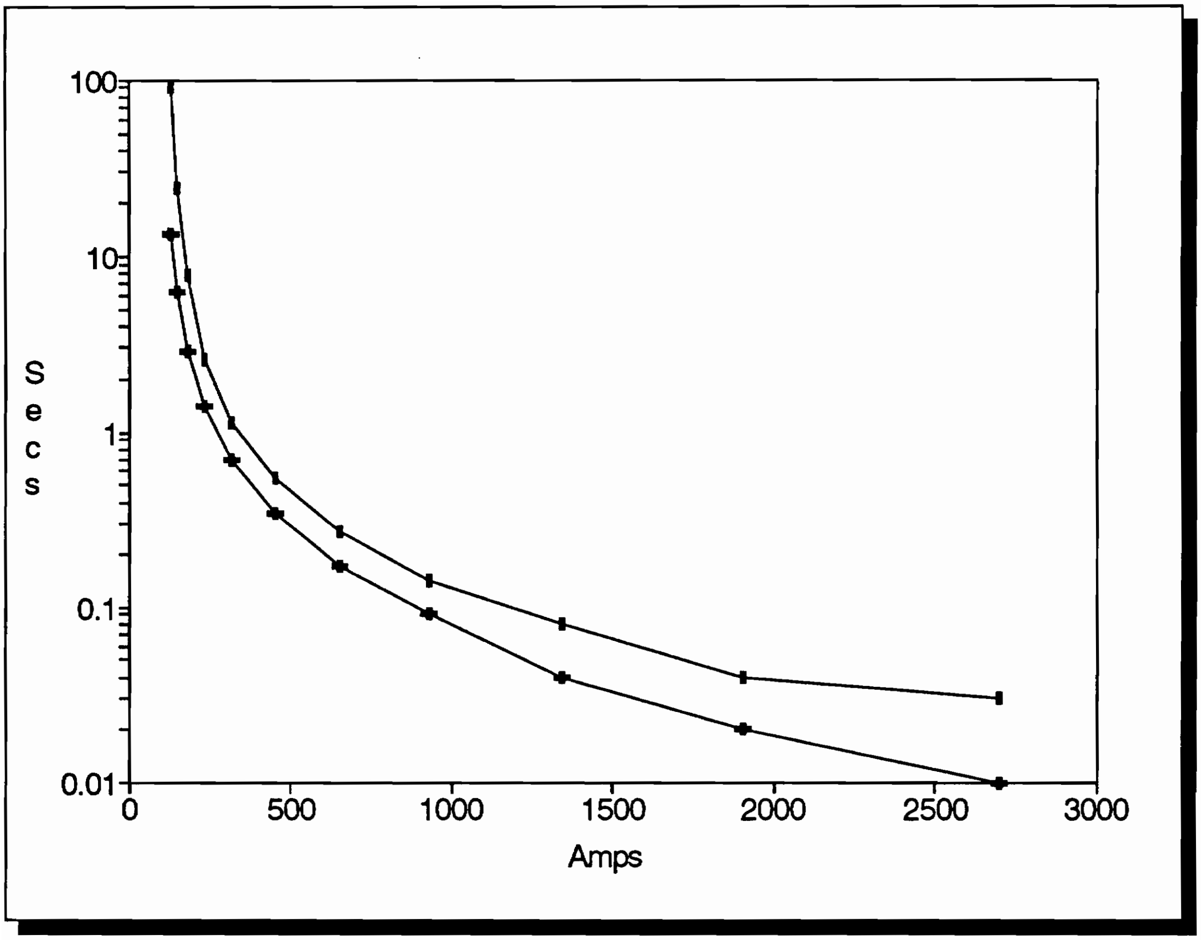

Figure 2.1. Fuse Time Current Characteristic Curve

The recloser also has a total number of operations sequence on each curve before it eventually Lockouts, or remains open, for a fault. A typical number of operations sequence is "2A - 2C." This implies that the recloser will operate twice on the lower curve, the "A" curve, and twice on the upper curve, the "C" curve, before the recloser lockouts. A recloser lockout occurs during permanent faults after cycling through its entire operating sequence on the lower and upper curves.

Line sectionalizers do not have any TCC curves associated with them. They are used in conjunction with automatic reclosers. Sectionalizers are switching devices that count the number of recloser operations. They are preset to open prior to a recloser lockout operation. This arrangement minimizes customer outages during faults.

2.2 Abbreviations and Symbol Definitions

This section presents definitions concerning symbols and abbreviations that are commonly used throughout this report. Table 2.1 contains symbol definitions, and Table 2.2 contains abbreviation definitions. Note that special typeface is used to denote symbols which, in general, have bold, italicized typeface. Abbreviations are given in all capital letters.

Table 2.1 Symbol Definitions

Symbol	Definition of Symbol
Ci	A logic variable that represents coordination rule *i*, i = 1, 2,... .
Pi	A logic variable that represents placement rule *i*, i = 1, 2,... .
Si	A logic variable that represents selection rule *i*, i = 1, 2,... .
Curve_Offset$_i$	A data structure member of the component object which is used in conjunction with the pointer to the Curve portion of the protective device Parts object. It is associated with each protective device component i , i = 1, 2, 3 ... .
Device_Offset$_i$	A data structure member of the component object which is used in conjunction with the pointer to the Device portion of the protective device Parts object. It is associated with each protective device component i , i = 1, 2, 3 ... .
Sptr_Curve	Starting pointer to an object of type protective curve that is also the first object in the linked list of objects of type protective curve.
Sptr_Device	Starting pointer to an object of type protective device that is also the first object in the linked list of objects of type protective device.
pCmp	Pointer to a Component object.
pFa	A data structure member of the Component object that is a pointer to a Fault Analysis Object, i.e. ***FA1, FA2, ... , FA14.***
FAi	Fault Analysis data objects that are attached to every component that is processed, i = 1, 2, ... 14.
pPo	A data structure member of the Component object that is a pointer to a Placement Object, i.e. ***PO1, PO2, ..., PO8***.
POi	Placement Objects that contain data results from placement function and are attached to every component that is a protective device location , i = 1, 2, ... 8.
SubVoltVary	The percentage value, that is specified by the designer, by which the substation source voltage is varied by Fault Analysis.
ZtoG	The value for ground impedance, that is specified by the user which is typically set at 40 ohms, used by Fault Analysis.

Table 2.2. Abbreviation Definitions

Abbreviation	Definition
CONF_ID	Configuration Index for the interconnected circuits
DPIM	Driving Point Impedance matrix
GRD	Ground
MAX	Maximum
MIN	Minimum
TCC	Time Characteristic Curve

CHAPTER 3

Literature Review

A literature search has been conducted in areas related to the design of protection systems. The literature has been grouped in the areas of General Principles, Computer Algorithms and Software, Expert System Applications, and General Integrated Solutions.

3.1 General Principles

The general principles involved in protection system design are presented in numerous manuals and texts. Standard practices have evolved from years of experience in the design and operation of protection systems. These references broadly cover the entire range of concepts and aspects behind protection system design. The work and cooperation between numerous engineers and professionals from industry, academia, and manufacturers have been responsible for the creation of a comprehensive knowledge base that presently exists for protection system design engineers. A chronological listing of these references follows with some brief discussion of their context.

In the 1950's the AIEE, a precursor of the modern day IEEE, produced two committee reports dealing with the usage of protective devices and some coordination principles [5, 6]. The reports detailed survey results from various electric utilities across the United States concerning common practices involving how they utilized and coordinated protective devices. The reports also listed problems that the utilities were experiencing with their protection system designs. Discussions and solutions for overcoming these problems were given in these reports.

In the late 1950's and early 1960's two technical papers described the protection system design practices of two utilities and their overall performance. Guenzel and Morris related the operation of the protection system design at Texas Electric Service Company.

Guenzel and Morris linked the operation of the protection system to the reliability of customer service [17]. Johnson and Meler described the protection system philosophies of American Electric Power Company, AEP, which discussed the practices observed when performing coordination between Breaker-Fuse, Recloser-Recloser, and Fuse-Fuse [18].

An IEEE Committee report in 1964 contained survey results from more than two dozen responding utilities [7]. Protection problems and discussions concerning methods for correcting these problems were presented in the report. The problem of blown fuses on feeders for temporary faults was presented in the report. Of special note was the reported problem of high impedance fault phenomena.

The common rules of thumb that presently exist for protection system design are attributable to work performed in the 1950's - 1960's era. The cooperation among multiple organizations during the time period lay the foundation for development of references that consolidated extensive information about designing protection systems. These reference sources provide proven techniques for overcoming a wide array of protection system problems. The most comprehensive of these reference sources are [1, 4, 8, 19].

3.1.1 Fault Analysis

One of the first steps in the design process is calculation of anticipated fault current levels. The classical method for calculation of fault currents is discussed by Gonen [14]. References [1] and [8] also give fault calculation examples using the classical approach. A somewhat different approach is presented by Kersting [20]. The major difference is that Kersting's approach uses actual system impedances and substation voltages to calculate the fault currents; whereas the classical approach uses sequence impedances and substation voltages to calculate the fault currents for the system.

The general purpose of the fault analysis study is to calculate fault currents due to different types of conditions. An example would be the fault current produced by a 3-phase bolted fault condition. For all different fault types considered a maximum and minimum fault current value is calculated for each circuit component. These values of maximum and minimum fault currents are utilized in conjunction with the operating characteristics of the protective devices.

3.1.2 Placement of Devices

At some point the designer must decide which locations need protective devices. The location of some protective devices is based on experience. To provide automatic reclosing capabilities either a breaker or recloser device is placed at all substations. All branching lateral line sections have fuses placed at their start. These two placement locations on the circuit are noted in all general protection system design references.

The presence of transformers on the main circuit, such as auto-transformers and tap changing types, creates havoc when performing device coordination. The problems of cold load pickup and inrush current are inherent problems with transformers, especially during restoration after circuit outages. Also, the type of transformer connection, such as wye-delta, can produce larger than expected fault currents due to phase shifting of faults currents passing through them [8]. These factors lead to the practice of effectively making all transformers located on the main circuits a protection zone boundary. Therefore, all power transformers on the main circuit typically have protective devices placed on both the primary, or source, and secondary, or load, sides. References 21, 22, and 23 discuss the merits and advantages of using current-limiting fuses with transformer applications.

3.1.3 Device Selection and Coordination

After calculating the fault currents for the circuit components and locating devices, the next step is to select protective devices. The type of device selected is dependent on various conditions such as the number of customers protected by the device, cost for the device, and circuit location. Fuses are the most widely used type of protective device due in large part to their cost and reliability [8]. For example, if the primary device's zone coverage is entirely underground service then a fuse would be selected for the device location. The reason is simple, underground circuits rarely experience temporary faults, and the cost of fuses is minimal when compared to the cost of reclosers.

All selected protective devices must coordinate with existing devices. Various approaches are utilized at this stage of the design process. Early protection system designers relied exclusively on light tables and transparencies of Time Current Characteristics curves for protective devices at this stage of the design. This manual coordination method is quite tedious and prone to human error. Numerous rules of thumb are often used to assist and speed up the process of device coordination [1]. The focus of most software applications involves this area. For example, Arkansas Power and Light uses an internally produced software package called PlotLog to check protective device coordination.

3.2 Computer Algorithms and Software

The computer as an aid to the process was quickly envisioned by protection system design engineers. One of the pioneering applications utilizing the computer for device coordination is presented by the paper of Albrecht et al. [24]. The paper shows how the computer can be used to relieve the designer of numerous calculations and aid the process. The approach is aimed at transmission relaying applications. A wide array of work and associated articles concerning computer-aided relay coordination followed Albrecht's paper. Program logic was implemented to allow interaction from the relay engineer in the approach used by Gastineau et al. [25]. The interaction from the relay engineer as the expert kept the program simple, and the size of the software manageable, for coordinating the relays. The work of Schultz and Waters showed that computer coordination enhances operation of the protection system [26]. The protection system performance improved when the relay engineer was allowed to analyze the protection scheme more thoroughly with the aid of computer generated calculations about different designs.

The work of Damborg and Ramaswami et al. in the area has included many facets connected with the coordination of transmission system relays as evident from References 27, 28, 29, and 30. Although the primary focus of the work was transmission relay coordination, the problems addressed are relevant to coordination of distribution devices. The problems of many simple calculations, very large data sets that need formal data management and algorithms that perform fault analysis and check coordination between devices are all necessary to protection system design work for distribution circuits. The approach used algorithms written in FORTRAN and relational database management to organize data.

Protection system design studies can require enormous amounts of data about the system. Data organization and handling can become a severe problem. The problems with the data handling of relay device setting files are presented by Zimering and Allen [31]. The approach was to computerize the relay setting file into a database so that pertinent data could be readily accessed by users.

Cauthen and McCannon provide information about using computer-aided protection engineering referred to as the CAPE System [32]. The CAPE System was a joint venture among a consortium of utilities in developing a protection engineering workstation environment. The software incorporates a database for handling the TCC curves associated with the protective devices. Additionally, the software performs fault calculations and provides graphical displays concerning device coordination.

Langhans and Ronat developed a graphical computer system for coordinating protective devices [9]. The system utilized the TCC curves of the devices to achieve coordination. Brown and Parker also used the TCC curves of the devices for coordination using a computer [33]. Brown and Parker modeled the TCC curves as piecewise linear curves consisting of a maximum of 20 data points. They concluded that the equation modeling of the TCC curves was not as practical or efficient as the piecewise linear curve method. The application of equation curve fit modeling of TCC curves is outlined by Smolleck [34]. The major advantage of this modeling approach is the computer disk storage space savings.

The topic of evaluating or qualitative measuring the performance of a protection system design has been suggested using a Figure of Merit by Juves, et al. [35]. The basic intent is to objectively evaluate different protection system design schemes by assigning a weighting factor or Figure of Merit to key operating features about the system. Some of these key operating features involve clearing speed during faults and customers or components effected during fault clearing operations. These key Figure of Merits serve as an alternative method that numerically evaluates device coordination.

The approach of Juves et al. somewhat parallels an issue raised in the work of Matulic and Lubkeman [2]. Matulic and Lubkeman addressed the problem of voltage flicker which is caused by the instantaneous operations of reclosers during temporary faults. Some customers were critical of system voltage flicker. Matulic and Lubkeman concluded that voltage flicker could be used in determining the reliability of the protection system design. In fact, some utilities have taken the instantaneous trip operations out of their reclosers on the circuit due primarily to customer complaints over this issue.

3.3 Expert System Applications

Expert systems are a subset of what is commonly referred to as Artificial Intelligence [36]. Expert systems can be programmed on a computer using knowledge from human experts in a given subject area. The created expert system can then be copied onto other computers and function without the assistance of the human experts. A human, on the other hand, requires an extended time period to become an expert on a subject, such as human experts in the area of protection system design.

An Expert System uses knowledge and rules to solve problems [37]. A typical knowledge base is a database that stores information. The inference engine uses rules and information to reach a conclusion about a problem [36]. Expert systems are increasingly utilized to solve complex problems in the area of electrical distribution systems, as noted by Kezunovic, et al. [38]. Kezunovic indicates that expert systems can easily be developed using computer languages such as Lisp and Prolog, but their execution speed is inherently slower than expert systems developed using C or FORTRAN. Hursch and Hursch explain that expert systems can be implemented using the interface between SQL and the associated relational database management system [39]. But, as Taylor and Lubkeman point out, "Expert Systems are not a panacea for every type of problem" [40]. They stress that only specific problems justify the effort and expense necessary to develop an expert system application. Protection system design problems warrant an expert system application. Human experts with valuable experience and knowledge are lost annually to retirement and job transfers in the protection system design area.

Pacific Gas and Electric implemented an expert system for coordinating protective devices [41]. Distribution engineers were interviewed to acquire knowledge for the expert system database. The expert system has over 300 rules implemented and uses 14 knowledge bases. The expert system software is used as a planning tool by design engineers.

A rule based coordination software system to evaluate protection schemes is presented by Mendis et al. [42]. The system's coordination rules can be modified to reflect the user's commonly implemented principles and practices. A library of TCC curves is provided to the user to facilitate graphical device coordination. Common device coordination such as Recloser - Fuse device coordination is checked by the software.

3.4 General Integrated Solutions

The protection system design requires analysis and access to enormous quantities of data. In order to relieve the engineer of handling redundant data elements the design needs to integrate various functions. This integration should transfer data output from one function into another function as input data. The necessary software functions are outlined that require an integrated solutions approach in the IEEE tutorial on protection system design [15].

The key elements are a relational database management system and the ability of algorithms to share data. The relational database stores circuit, protective device, and analysis data. The management system is used to control data flow. The sharing of relevant data among algorithms promotes easier software development and faster design of the protection system. The graphical display capability fosters friendly user interfaces and more understandable interpretation of results. Maghdan's approach is highly integrated as noted by references [16] and [43] and parallels the method outlined by IEEE. Maghdan implemented rule based algorithms for placement of devices, building a table of coordinated devices, and selection of coordinated devices based on the fault currents at circuit locations.

CHAPTER 4

The DANE Engineering Workstation

4.1. Overview

The goal of this chapter is to briefly review those DANE engineering functions that are used in conjunction with protection system design work. The intent is not to completely review the DANE engineering workstation. An in-depth overview of the DANE engineering workstation is provided by References 44 and 45. Thus, only a brief review of the relevant DANE engineering functions is presented in this research report.

The DANE workstation has been designed to study electrical power distribution systems. The DANE workstation has been developed under the OS/2 operating system. C is the standard software language in which all engineering functions are written for the DANE workstation. The power of the C Language is derived from its data structures and pointers [46]. DANE uses the pointers to efficiently manipulate the data in memory.

DANE uses a relational database management system for data storage. SQL, Structured Query Language, statements are used in conjunction with relational database management system. SQL statements facilitate relational database transactions [39]. SQL statements may also be embedded inside software written in the C language forming what is referred to as ESQL, or Embedded SQL, software.

DANE presently has engineering functions that, to name a few, perform fault analysis, power flow calculations, circuit reconfigurations, reliability analysis and restoration operations. DANE provides graphical input and output capabilities for both the software developer and user. The user is able to graphically construct engineering schematics that represent electrical distribution circuits. The user may graphically display output results obtained from the DANE engineering functions.

4.2. Data Sharing Between Functions

In the DANE workstation each piece of distribution equipment, or part, is stored in an appropriate database table. For example, all various transformer type parts are stored in the Transformer table. Each row in the Transformer table row represents a distinct transformer type; and the columns, that comprise a row, contain data describing the transformer type. All of the parts associated with the distribution system collectively form the Part objects of DANE. These Part objects are utilized by DANE when circuit schematics are graphically constructed by the user.

When DANE is activated pertinent data, stored in numerous database tables, is loaded into various data structures, that are created and reside in computer memory, i.e. RAM. This process, of loading the data structures residing in the RAM, emulates an in-memory database while DANE is running. These data structures are accessible and shared by all software developers and functions in the DANE environment. It also greatly enhances the execution speed of the software. The sharing of data also promotes faster software development.

The sharing of data among functions is implemented via the linking of objects. An object is a particular instance of a data structure that exists in memory, whereas a data structure is a specification describing a set of related variables [48]. In other words, a data structure is a template that is used to form an object at a location in computer memory.

Component objects contain information common among distribution equipment and are linked via pointers to Part objects [47]. A separate component object exists for each piece of distribution equipment that is modeled in a circuit schematic. Thus, circuits are built in computer memory with component objects. Examples of the different types of Part and Component objects are shown in Figure 4.1. As illustrated in Figure 4.1, a Line / Cable Component object is created from two Part objects, the Conductor and Construction Part

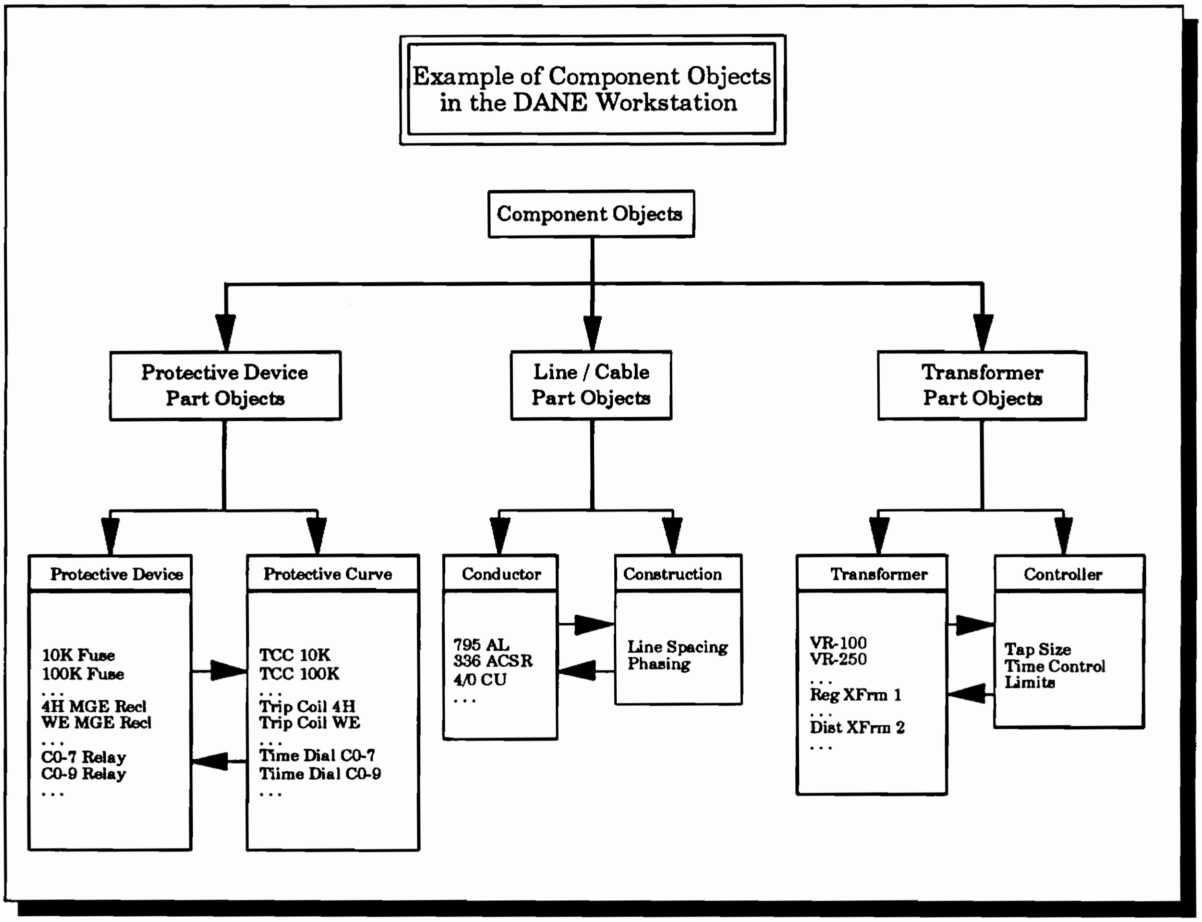

Figure 4.1. Example of Part Objects in DANE

objects. The Conductor Part objects contain information describing the properties associated with the line and cable conductors, and the Construction Part objects contain information regarding items such as the line spacing between conductors, the phasing of the conductors, overhead or underground line construction, etc.

DANE manages the data associated with distribution circuit models. The circuit data changes dynamically whenever the user makes graphical modifications to existing circuit schematics. The software developer has access to the circuit data. Yet, the management of the integrity of this data is the not the responsibility of the software developer. The management approach DANE utilizes, regarding the data associated with the distribution system, allows software developers to share common data among engineering functions [47].

4.3. Relevant Engineering Functions

This section presents an informative discussion concerning those engineering functions that are critical to protection system design. During the design of a protection system, data is required from several engineering functions. In particular, the data from fault analysis, power flow, and circuit configurations must be obtained during the initial phases of the design process. Thus, the key functions of fault analysis, power flow, and circuit configurations are discussed regarding how they supply the necessary data to the protection system designer.

4.3.1. System Data Input and Data Manipulation Using Pointers

The starting point for most protection system designs is the data from a fault analysis study. At this juncture some background information is presented regarding the necessary input system data required by the fault analysis function. The fault analysis function must have access to the impedance data associated with each circuit component. Additionally, the operating voltage level data of the substation supplying the circuit components must be available to the fault analysis function.

In the DANE workstation, the majority of the input data for the fault analysis function are contained in the Component object. Table 4.1 shows the relevant data elements associated with a Component object that are utilized by the fault analysis function. Table 4.1 gives data elements and a brief definition concerning their usage by the fault analysis.

The Substation data structure contains data about the operating voltage level of substations. Additionally the internal impedance data of the substations, as seen by feeder circuits, is contained in the Substation data structure. Note that data contained in the Substation data structure may be accessed by using pointer manipulation together with associated data from the Component object. The procedure involves using the *Offset* data from the Component object defined in Table 4.1 and, the starting pointer associated with the Substation data structure.

The remainder of this section presents two examples that demonstrate how DANE functions use pointers and data from Component objects to access data within other data structures. The specific examples presented illustrate how functions in DANE use pointers to manipulate data structures. One example shows how substation voltage levels are determined, and the other example shows how breaker current ratings are obtained using pointers.

The first example illustrates how to determine the operating voltages for a substation, defined as ***SubVolts***. Note that ***SubVolts*** is a 3-element array that represents the per phase voltage at the substation. The data for all substations is stored in the Substation Table. Each substation has a unique order number associated with it. The data from the Substation Table is loaded into the Substation data structure when DANE is activated. Additionally, a pointer to the start of the Substation data structure is set which is defined here as ***SptrSub***, that points to the starting location of the Substation data structure in memory.

When a circuit schematic is built a substation must be selected to supply power for the circuit. Upon selection, the only information concerning the substation that is stored in the associated Component object is its unique order number. This unique order number is stored as *Offset* in the Component object. Using *Offset* from the Component object together with ***SptrSub***, the correct substation can be located in the Substation data structure. ***SubVolts*** can then be determined using the arrow operator, ->, to the *Voltage* data. The C language code necessary to determine ***SubVolts*** is given as

SubVolts = (***SptrSub*** + *Offset*) -> *Voltage* . [4.1]

The last example shows how to determine the amperes rating for a breaker defined as ***BrkAmps***. Similar to the discussion presented in the first example, all the data associated with breakers is stored in Breaker Table and loaded into a Breaker data structure. A starting pointer is set to locate the start of the Breaker data structure, which is defined as ***SptrBrk*** .

Using ***SptrBrk*** and *Offset* in the Component object, the value for ***BrkAmps*** is determined using the arrow operator, ->, to the *Amps_Rating* data. The C language code required to find ***BrkAmps*** is given as

BrkAmps = (***SptrBrk*** + *Offset*)-> *Amps_Rating* . [4.2]

As demonstrated by the discussion and examples presented in this section, the strategic usage of pointers and Component object data enable DANE software functions to readily access pertinent data.

Table 4.1. Relevant Data in the Component Data Structure to Fault Analysis

Variable	Definition of Usage in Fault Analysis
CmpType	identifies the type of component, such as line or capacitor, and is used to search the appropriate data structure.
CxMZ	contains the 3 by 3 complex matrix impedance representation for each component. This matrix is used in the calculation of the DPIM from the substation for each component.
DPIM	represents the 3 by 3 complex Driving Point Impedance Matrix calculated for a component by the fault analysis function in DANE.
ITap	is an array of 3, that represents the value for a component's impedance reflection coefficient per phase. It is used to reflect the impedance from any location back to the substation. The value is determined by the ratio between the primary and secondary transformer windings that exists between a component and the substation. Note, that if no transformers exist on a circuit then all components would have a value of 1.0 for each element in the ITap array.
MaxFaultTyp	indicates which fault condition produced the maximum fault current through a component; the value is set by Fault Analysis during the calculations when considering the substation.
Phases	indicates the number of phases present and their arrangement for a component.
Offset	is the value that represents the offset in the appropriate data structure. The value corresponds to the row number in the part database table. For similar devices, such as capacitors, the row number is unique in the database table.
TieFlow	indicates the direction of current flow through a component.
Bptr	is a pointer from the active component to its Backward component in the circuit topology.
Fptr	is a pointer from the active component to its Forward component in the circuit topology.
FPptr	is a pointer from the active component to its Feeder Path component in the circuit. The Feeder Path is based upon the physical connections of the circuit. The Feeder Path component is defined here to be that component which supplies power, or is the feeder, for the active component.
pCmp	is a pointer to a Component Object.

4.3.2. Fault Analysis

In general, fault analysis calculates anticipated fault current levels throughout the distribution circuits involved in the study. A brief review is provided of the fault analysis developed in conjunction with this research for the DANE workstation. The methodology and approach used by the fault analysis developed for DANE in calculating fault currents is similar to that described in the work of Kersting [20]. A major difference however is that Kersting's approach uses FORTRAN, while the fault analysis for DANE, uses C. However in both methods, the general approach is to develop an impedance matrix that is used in conjunction with the substation voltage level in determining the anticipated fault current levels. Unless otherwise noted, all future references to fault analysis will imply the fault analysis function developed for the DANE workstation.

The impedance matrix represents the impedance that exists from the substation source to any component location on the circuit that is supplied by the substation. An impedance matrix must be calculated for each circuit component. The impedance matrix used in DANE is a 3-by-3 complex matrix. The impedance matrix calculated at a given circuit component in effect determines, or drives, the fault current level, and is referred in the remainder of this report as the ***DPIM,*** Driving Point Impedance Matrix.

To determine the ***DPIM*** of each circuit component the fault analysis function must process the topology of the circuit using Component objects. The pointers in the Component objects, that are described in Table 4.1, are used to analyze the topology of the circuit. The process, of using pointers associated with component objects to analyze the topology of a circuit, implements what is referred to as a circuit trace [47]. The type of pointer used determines the nomenclature for the circuit trace.

For example, if the Feeder Path pointer is used to analyze the Component objects associated with the circuit, then a Feeder Path circuit trace is implemented by the process. The last component encountered in a Feeder Path circuit trace is always a substation component. An example of Feeder Path circuit trace, ***FPCT***, is given using the circuit schematic shown in Figure 4.2. Note that the example presented is defined in shorthand notation by referring to the component numbers of Figure 4.2. Using the circuit diagram shown in Figure 4.2, a ***FPCT*** from component 12 back to the substation, or component 0, would yield

$$\{\boldsymbol{FPCT} : 12\} = \{ 11, 9, 7, 6, 2, 1, 0 \} \ . \qquad [4.3]$$

Similarly, a Forward circuit trace, ***FCT***, implemented from component 2 to the ending circuit component, component 14, is given as

$$\{\boldsymbol{FCT} : 2\} = \{ 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 \} \ . \qquad [4.4]$$

Fault analysis uses Forward and Feeder Path pointers to calculate the ***DPIM***. All circuit components are analyzed using a ***FCT***. To determine each component's ***DPIM***, the impedance value for the component is added to the ***DPIM*** of its feeder path component during the ***FCT***. The impedance value of a component, referred to here as ***Zcomp***, is calculated as shown

$$\boldsymbol{Zcomp} = (\boldsymbol{pCmp} \text{ -> } \boldsymbol{CxMZ}) * (\boldsymbol{Ptr} \text{ -> } \boldsymbol{ITap}) \qquad [4.5]$$

where ***Zcomp*** is a 3-by-3 complex matrix, and the variables ***pCmp***, ***CxMZ*** and ***ITap*** are defined in Table 4.2.

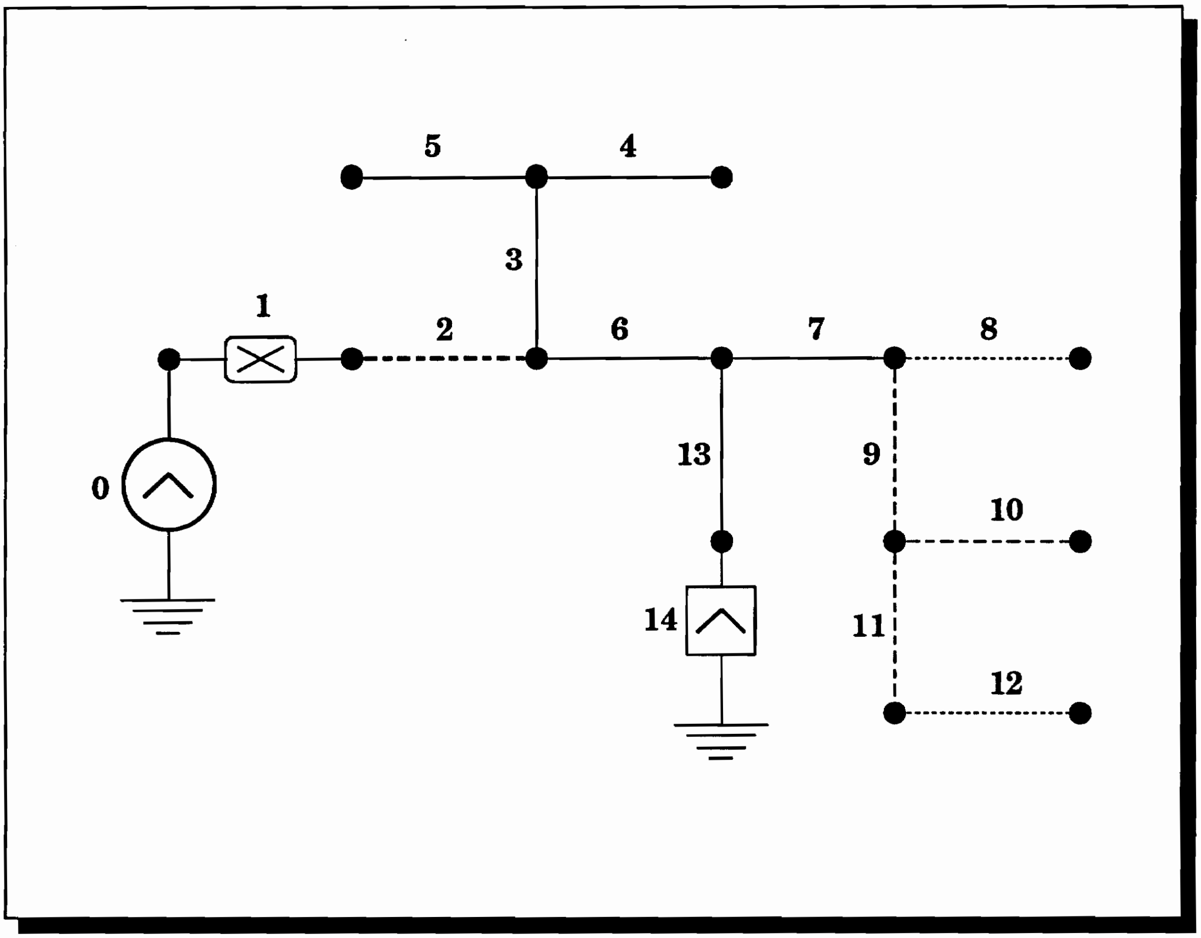

Figure 4.2. Example Circuit Schematic

The **DPIM** of the feeder path component is determined using the Feeder Path pointer for the component as shown

$$\boldsymbol{ZFPcomp} = \boldsymbol{pCmp\text{->}FPptr\text{->}DPIM} \qquad [4.6]$$

where **ZFPcomp** is a 3-by-3 complex matrix.

The value of the component's **DPIM** is determined from the results obtained in [4.5] and [4.6] as shown

$$\boldsymbol{DPIM} = \boldsymbol{Zcomp} + \boldsymbol{ZFPcomp}\ . \qquad [4.7]$$

The calculations shown in Equations [4.5], [4.6] and [4.7] involve complex matrices; thus the addition shown by [4.7] indicates complex matrix addition operations.

After determining the **DPIM** for all circuit components, fault analysis calculates the induced faults currents basically using Ohm's Law, $I = V/Z$, as shown:

$$\mathbf{I_F} = [\boldsymbol{DPIM}]^{-1} * \boldsymbol{SubVolts} \qquad [4.8]$$

where I_F is the array of calculated fault currents. **SubVolts** is the array of substation voltage given by Equation 4.1 and, **DPIM** is defined by Equation 4.7. All of the quantities shown in Equation 4.8 are complex values.

The **FPptr** of all substations is NULL and, the **DPIM** for a substation is equal to **CxMZ** of the substation. However, the **CxMZ** for a substation component may be zero since an impedance value for the substation is unknown. In this case, the **DPIM** for the substation component would be zero, and fault analysis would not attempt any calculations and proceed to the next component; but, if the **DPIM** of any component other than a substation is zero, fault analysis halts execution and sends the user appropriate error messages. This prevents software crashes due to division by zero errors in later fault current calculations.

Eleven different type of fault conditions are considered by fault analysis as shown in Table 4.2. The number of phases and their arrangement, such as ABC or BC phases, is determined for a component object using pointer access to the variable *Phases.* The value of *Phases* determines which of the eleven types of fault conditions indicated in Table 4.2 need to be analyzed. If, for instance, *Phases* indicates an A-Phase line section, then only one fault condition is analyzed -- the A-phase ground fault. All eleven types of fault conditions are evaluated only for 3-phase line components.

Some component types do not have fault calculations performed for them and are skipped over by fault analysis. Fault calculations are only performed for line, cable, transformer, cogenerator, and substation components in the circuit. When a component is skipped, fault analysis sets the value of its fault currents equal to the value of its feeder path component's fault currents. The type of component is determined using pointer access to the variable *CmpType*, where the value indicates the type of component.

The calculated fault currents for a component are effected by two other global, variable parameters. One is the voltage variance percentage at substation source, referred to as ***SubVoltVary.*** The user is able to set the value for ***SubVoltVary***. If the value of ***SubVoltVary*** is non-zero, fault analysis will use the value to vary the substation voltage. Thus, fault analysis essentially calculates fault currents for two substation operating voltages, which are the maximum and minimum operating ranges. This feature permits the user to model voltage variations at the substation.

The second global, variable parameter is the ground impedance , referred to as ***ZtoG***, and is typically set at 40 ohms. However, the user may specify a different value for this parameter. The value of ***ZtoG*** is added to the diagonal elements of the component's ***DPIM*** when considering line-to-ground type of faults. The value of ***ZtoG*** significantly affects the calculated magnitude of fault current. As noted previously in Chapter 3 of this report, high impedance faults are of special concern and occur when the value of impedance to ground, as seen by a fallen energized conductor, is extremely large in magnitude; the value of ZtoG will have a profound effect on the value of impedance to ground seen by a fallen line conductor.

As each component is being processed by fault analysis, a set of maximum and minimum fault currents is developed for the component. Additionally, on all tie-line components, the value of *TieFlow* is checked to determine current flow direction. If the component is not a tie-line or the direction of current flow is normal, the set of maximum and minimum fault currents developed is referred to as the FORWARD set; otherwise, the direction of current flow is reversed, and the set is referred to as the REVERSE set. Thus, two sets of maximum and minimum fault currents exist for tie-line components.

Table 4.2. Type of Fault Conditions Considered by Fault Analysis

Fault Type	Description
ABC-Bolted	Three Phase Bolted Fault
ABC-to-Ground	Three Phase Fault to Ground
AB-Fault	A Phase to B Phase Fault
AC-Fault	A Phase to C Phase Fault
BC-Fault	B Phase to C Phase Fault
A-to-Ground	A Phase to Ground Fault, with ***ZtoG*** non-zero value
B-to-Ground	B Phase to Ground Fault, with ***ZtoG*** non-zero value
C-to-Ground	C Phase to Ground Fault, with ***ZtoG*** non-zero value
A-Fault	A Phase Fault, with ***ZtoG*** zero value
B-Fault	B Phase Fault, with ***ZtoG*** zero value
C-Fault	C Phase Fault, with ***ZtoG*** zero value

During fault conditions, cogeneration sources contribute to the induced fault currents on circuit components. If any cogeneration source exists, fault analysis calculates fault currents for the circuit components due to the cogeneration source. For this case, the cogeneration voltage source is the reference for the ***DPIM***. The ***DPIM*** must be re-evaluated based upon the circuit location of the cogeneration source. The procedure uses the existing value of each component's ***DPIM*** that has been calculated previously when considering the substation voltage source.

Only the fault condition, specified by *MaxFaultTyp*, is considered during the calculation of fault current due to the cogeneration source. The calculated fault current contributions are added to the existing maximum fault current values; this assumption is based on the fact that most utilities do not allow cogeneration sources to remain online whenever the substation is offline.

4.3.3. Power Flow

Data is also necessary concerning the power flow, or load current, on the circuits involved in the protection system design study. The value of peak load current must be taken into account by the protection system design. As Reference 1 indicates, the predominant cause of improper protection system operation is due to load growth.

A load growth factor parameter is associated with every circuit object and is used to compensate for future load growth of the circuit. The load growth factor parameter is used to scale, or multiply, the value of peak load current. The scaled value of peak load current is theoretically its maximum attainable value. Thus, the peak load current is never expected to exceed this value during the lifetime for the given circuit construction.

Since a fault may occur during a peak load condition on the circuit, the value of peak load current must be added to the maximum fault current level of the component objects.

The value for peak load current is also crucial concerning two other aspects of the protection system design. First, the minimum pickup, of both the primary and backup protective devices protecting a zone, must always be above the peak load current level threshold within that protection zone. Second, if the peak load current exceeds the minimum fault current level within a protection zone, a ground sensing device must be used to provide minimum fault current level protection within that zone. The topic of ground sensing devices for minimum protection, is more thoroughly examined and discussed later in Chapter 6 of this report.

A detailed explanation about the power flow function developed for the DANE workstation is provided by references [10], [50].

4.3.4. Circuit Configurations

To properly design the protection system for interconnected circuits, data must be obtained concerning their circuit configurations. The different circuit configurations are due to different switching configurations among the interconnected circuits involved in the study. All the different circuit configurations must be analyzed during the initial phases of the design. This analysis must include a fault analysis and power flow study for each configuration of the interconnected circuits.

It is during this stage of the design that tie-line data is developed for the circuits. As noted previously, tie-lines are those sections of the interconnected circuits that experience bi-directional current flows which consist of both fault and load current flows. The terminology of Forward and Reverse current flow is used to account for this bi-directional current flow. Thus, tie-lines will have both a Forward and Reverse set of Maximum and Minimum fault currents that they may experience.

From these two sets of Maximum and Minimum fault currents an Absolute set of Maximum and Minimum fault currents are developed during the design. The Absolute Maximum fault current is defined as the maximum value obtained when comparing the Forward and Reverse Maximum. Similarly, the Absolute Minimum fault current is derived from the Forward and Reverse Minimum fault currents. The Absolute - Maximum and Minimum, Forward - Maximum and Minimum, and Reverse - Maximum and Minimum sets of calculated fault currents are stored with every component object. This data is accessible for other software applications.

In DANE, the circuit configurations may be developed by two methods. The first method is to use the switching patterns developed by the reconfiguration function for the interconnected circuits. These switching patterns simply depict which switches should be opened and which switches should be closed thereby creating the configuration for the interconnected circuits. The reconfiguration function determines both seasonal and daily switching patterns [10].

Table 4.3. Switching Configurations Patterns

CONF_ID	SW 117	SW 234	SW 354	SW 789	SW 857
-1	Closed	Opened	Opened	Closed	Opened
1	Closed	Closed	Opened	Closed	Closed
2	Opened	Closed	Closed	Closed	Opened
3	Opened	Closed	Closed	Opened	Closed
4	Closed	Opened	Closed	Closed	Closed

The second method uses the data existing in the Switching Configurations Table. The Switching Configurations Table is an individual database table within the DANE workstation. Table 4.3 shows a representation of the Switching Configurations Table with typical data. The first column indicates the configuration number. All of the remaining columns indicate the status of the switch, either opened or closed.

The first row of the Switching Configurations Table is used as a label by DANE to manage the switches within the distribution system. For the example shown in Table 4.3 as indicated in columns two through six of row one only five switches, i.e. SW117, SW234, SW354, SW789, and SW857, exist in the system. For the example given in Table 4.3, four switching configurations exist as denoted by rows two through five. For each of these configurations the status of the switches is indicated in columns two through six. The first column of the table, labeled CONF_ID, is used to identify the configuration. Note that for the first row in Table 4.3, the CONF_ID is set to -1.

A CONF_ID of -1 indicates that this is the normal, or base, configuration for the circuits. Note that when developing tie-line fault current data the base configuration is used to determine the Forward fault current directional flow. When other circuit configurations are analyzed, the direction of fault current flow on all tie-lines must be checked against the direction established by the base configuration. The Reverse fault currents occur when the directional fault current flow reverses from that of the Forward fault current.

Using DANE the switching patterns for a given configuration of interconnected circuits may be developed and stored in the database for later reference. Using the data from the Switching Configurations Table the protection system design study is able to analyze all possible circuit configurations. This method is more attractive since it has a much faster execution speed -- once the Switching Configurations Table is built analysis time by the reconfiguration function is not required -- and it is possible to develop circuit configurations that the reconfiguration function would not develop during its analysis. Thus, the designer/user has the option of using either configuration data created by the reconfiguration function or data from the Switching Configurations Table.

4.4. Testing of DANE Workstation Functions

Arkansas Power and Light has modeled over 100 distribution circuits at its Hot Springs Division using the DANE workstation. Most of the relevant parts data concerning the Hot Springs Division distribution circuits have been loaded into the DANE database. The power flow and reconfiguration functions developed for DANE have been tested and utilized by the engineering personnel at Hot Springs, Arkansas. Arkansas Power and Light has used the results from DANE to perform seasonal reconfigurations of some of the interconnected circuits at its Hot Springs Division.

As part of this research, data from fault analysis has been compared to data obtained from the software developed in-house by Arkansas Power and Light called DFA (Distribution Feeder Analysis). A comparison was made using the calculated fault currents from DANE and DFA. This comparison included five distribution circuits from the Hot Springs division. The comparison of the calculated fault currents from DFA against those from fault analysis yielded results that indicated the values of fault currents from Fault Analysis were within 5% of those from DFA.

4.5. Key Features Summary of Fault Analysis Function

A summary of the keys features incorporated by the fault analysis function include the following --

* Fault current calculations are performed in memory without any database queries which enables the function to perform much faster execution.
* Fault analysis is able to manage bi-directional fault current flows.
* Affects of cogeneration sources are considered by fault analysis
* Actual system impedances utilized to determine fault currents.
* The eleven different fault conditions that are described in Table 4.2. are used in developing the ABSOLUTE, FORWARD and REVERSE sets of Maximum and Minimum fault currents.
* The user is able to select and vary earth impedance value.
* The user is able to model variations of the substation voltage levels.
* Power flow results are incorporated in calculated fault currents.
* Multiple configurations of interconnected circuits are evaluated from switching data that is either derived by the reconfiguration function or from the switching configurations table.
* The fault analysis function developed for DANE is a dual purpose function in that it may be accessed by other analysis functions or it may be run as a stand alone analysis function.

CHAPTER 5

Relational Modeling of Protection Devices

5.1 Introduction

Protection systems are designed, primarily, using three type of protective devices, namely fuses, reclosers and relays. There is, of course, auxiliary equipment used in conjunction with some of these protective devices, such as current transformers with relays, breakers with relays and sectionalizers with reclosers. But only fuses, reclosers and relays have TCC curves associated with them. As noted in Chapter 2 TCC curves define the operating characteristics of protective devices. However, additional data is required to adequately model protective devices.

Since a protective device is an integral component of the circuit, it must be capable of withstanding the operating conditions imposed by the circuit environment. A protective device must operate at the circuit voltage level; it must be capable of interrupting the maximum fault current within its protection zone, and if the protective device is a fuse or recloser, the load current must flow through it without damaging the device or creating false operations by the device. A protective device must be rated based on both circuit constraints and anticipated fault currents. The costs associated with protective devices are based on their withstand ratings. Obviously, for a given class of protective devices the costs increase as the withstand ratings increase. Thus, it is necessary to consider more then merely the TCC curves data associated with protective devices when designing a protection system. Data pertaining to ratings and costs as well as TCC curves must be incorporated and examined by the designer.

Most utilities have built-up a vast collection of protective device data that must be maintained. Quite often utilities acquire and install protective devices from various manufacturers. The eventual result is a diverse assortment of protective devices scattered throughout the electrical system. While some of these protective devices may be discontinued or replaced with improved device types, the utilities must nevertheless maintain the data concerning those that are still in service. Most electric utilities have a wide assortment of protective device data to manage.

To manage and maintain its protective device data, most utilities have implemented some type of computerized data storage. The size of this data can be enormous and require large amounts of computer storage. A main goal of the protective device model developed as part of this research is to compact the data, thereby reducing its storage requirements. The next section presents the methodology used in developing the protective device model.

5.2. Relational Database Model

DANE utilizes a relational database management system for data storage. Relational databases tend to compact data and reduce the amount of storage space required on computer hard-disk. However, hard-disk access to retrieve data stored in a relational database can be time consuming for software applications [47]. Thus, it is necessary to optimally compact the data required to model protective devices. This will facilitate the loading of the protective device data into main memory when DANE is activated by the user.

The relational database model developed as part of this research incorporates the pertinent data associated with protective devices. However, before the relational database protective device model is presented, some of the key underlying issues that were considered during the development of the model are presented.

5.2.1. Key Issues Effecting Model Development

The first issue deals with the modeling of the dissimilarities between the TCC curves associated with the protective devices. Fuses have only one set of TCC curves that are used in describing their operation, the Pickup and Clearing Curves. Reclosers have multiple TCC curves from which the designer may pick a set for the Fast Trip and Lockout/Delayed Trip curves. Different recloser classes from a single manufacturer will have vastly different possible combinations. For instance, a type "H" class recloser may have 4 possible Fast-Lockout combinations; yet a type "WE" class recloser may have 20 possible combinations. Relays have a family of TCC curves associated with them, but they operate based upon a single TCC curve within this family. This single TCC curve is affected by the time dial setting chosen for the relay. Research by engineers involved in protection system design indicates that the time dial setting does not linearly scale the time portion of the TCC curves associated with a relay. Furthermore, for a specific relay type multiple "Styles" will exist, and each "Style" will have a different family of TCC curves associated with it. Thus, the TCC curve of a relay is dependent on both its time dial setting and "Style."

Another issue to consider is the relationship between recloser trip coil ratings and relay tap settings in regards to their effect on the TCC curves. The trip coil rating of a recloser in effect linearly scales the amperes values of the TCC curves associated with it. A specific recloser will have numerous possible trip coil ratings. As the recloser's trip coil rating is increased so does the value for amperes, but the operational time value is unaffected. Thus, the TCC curves are moved to the right along the amperes axis as illustrated in Figure 5.1. Figure 5.1 shows this effect on a typical recloser's TCC curves; as the trip coil rating is doubled the recloser's operational amperes value is doubled. This is illustrated in Figure 5.1 which shows that **A2** is double value of **A1**. As the value of a relay's tap setting is increased, the same effect is exhibited on its operational characteristic. The relay's family of TCC curves are shifted right, increasing only its amperes value.

As demonstrated by these underlying issues, the method of modeling protective devices is not straightforward, and various factors must be taken into consideration. While all of the protective devices have TCC curves describing their operation only fuses have a

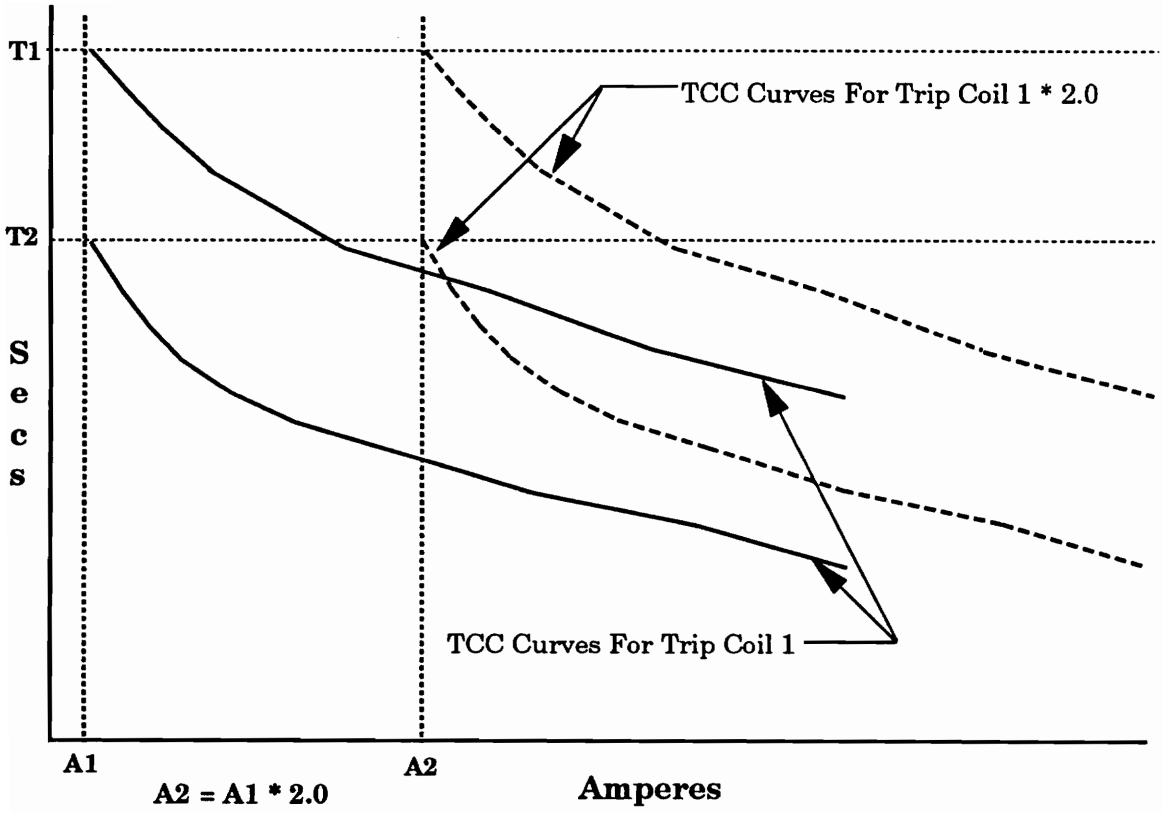

Figure 5.1. Effects of Trip Coil Rating on a Recloser's TCC Curves

single set. If all of the protective device data was stored in a single table, the size of the table would be enormous due to the redundancy in the data. This approach is very inefficient and unacceptable in the DANE environment.

5.2.2. The DANE Relational Protective Device Model

For this research, two relational database tables were implemented in DANE to model protective devices. The method eliminates redundant data and compacts the data. One table is referred to as the Curve Table and contains the TCC curves associated with a protective device, and the other table is referred to as the Device Table and contains the remaining pertinent data. Tables 5.1 and 5.2 present the variable names of the column data and their associated definitions for the Device and Curve Tables, respectively. Data for fuses, reclosers, and fuses are stored in each of these two tables. Storing all device types together simplifies both database queries and the organization of data when it is loaded into computer memory by DANE.

Splitting the data between the Device and Curve Tables significantly reduces the data storage for reclosers and relays. Since recloser trip coil ratings and relay tap settings only linearly scale the amperes values of their associated TCC curves as discussed previously, the model exploits this assumption to compact the data. The model compacts the data by storing all trip coil ratings or tap settings for a single recloser or relay, respectively, in the ***Scale*** array as a single entry in the Device Table. For example, consider a recloser with 12 trip coil ratings and 4 sets of operating TCC curves. If the data for the recloser was stored in a single table it would require 48 entries, 4 x 12 entries, but using two tables it requires 4 entries in the Curve Table and only a single entry in the Device Table. In the case of a relay with 5 styles, 8 tap settings, and 11 time dial settings for the TCC curve, the storage required in a single table would be 440 entries, 5 x 8 x 11; yet split between two

Table 5.1. Device Table

Variable	Definition of Column Contents
Code	The user defined name for the protective device.
Style	The user defined name for family of curves associated with a relay or recloser class.
Device	A unique number associated with the device which is the row number of the device in the Device table.
Type	Indicates whether the protective device is of type fuse, recloser, or relay and if it is a phase or ground type device.
Family	A number associated with family of curves which applies to a relay or a recloser.
Curve	The number for the starting row in the Curve Table that contains all curves associated with a protective device.
Volt_Rating	The specified operational voltage range value for the protective device.
Amps_Rating	The continuous current rating value of the protective device, if it is a fuse or recloser.
Interrupt	The interrupting rating value of the protective device, if it is a fuse or recloser.
Scale[j]	An array containing either the trip coil ratings for reclosers or the tap settings for relays: where Scale[j] = jth value in the array.
Cost	The purchase cost for the protective device.
Maint_Cost	The annual maintenance cost associated with the protective device.
Failure	The annual statistical failure rate for this type of protective device.
Repair	The average time required to either repair or replace a protective device of this type.

Table 5.2. Curve Table

Variable	Definition of Column Contents
Selector	The name used in the curve selection for a relay or recloser.
Curve	A unique number associated with the curve which is the row number of the curve in the Curve table.
Type	Indicates whether the protective device is of type fuse, recloser, or relay and if it is a phase or ground type device.
Family	A number associated with a family of curves which applies to relay or recloser.
Lower	The number of points stored for the first TCC curve in the CT array.
Upper	The number of points stored for the second TCC curve in the CT array.
CT[i, j]*	Two dimensional array of points from the TCC curves: where CT[0, j] = jth current value and CT[1, j] = jth operation time value.

* For each element of the array, a separate column is implemented in the table.

tables the required storage is only 11 entries in Curve Table and 5 entries in the Device Table.

The Curve and Device Tables are relational linked together using "Keys" in the tables. The ***Device*** variable in Table 5.1 and the ***Curve*** variable in Table 5.2 are unique keys [39]. These variables are vital to in-memory management of data. The ***Curve*** and ***Family*** variables in the Device Table are foreign keys into the Curve Table.

In the Curve Table the array ***CT*** is used to store the TCC curves associated with a device. Depending upon the type of protective device, the array ***CT*** that is stored in each row of the Curve Table contains either one or two TCC curves. For fuses and reclosers two curves are stored, whereas for relays only a single curve is stored. The Pickup and Clearing curves are stored for fuses. The Fast Trip and Lockout/Delayed Trip curves are modeled for reclosers.

The ***Family*** variable is applicable to both relays and reclosers. A given class of relay may have multiple families of curves. A given recloser has multiple pairs of operating curves. A unique integer is assigned to ***Family*** for each different family of curves that may be associated with a relay. For a specific class of relay, ***Family*** may have several different values, but, for a given recloser, ***Family*** has only a single value.

For fuses there is a one-to-one relationship between rows in the Device Table and rows in the Curve Table. Only the fuse ***Code*** and ***Type*** are needed to uniquely specify a fuse. Given a fuse ***Code*** and ***Type*** its corresponding ***Curve*** variable may be determined from the Device Table. For fuses the ***Curve*** and ***Family*** variables are set equal. The ***Family*** variable may then be used as a foreign key into the Curve Table to select the Melting and Clearing curves for the fuse.

For reclosers, there is a one-to-many relationship between rows in the Device Table and rows in the Curve Table. To select a specific recloser, the recloser ***Code***, trip coil rating , and a pair of operating curves (i.e., AB, AC, etc.) must be specified. For a specific type recloser such as "H", all of the trip coil ratings are stored in the ***Scale*** array variable.

With reclosers, the variables ***Code***, ***Type***, and ***Scale*** may be used as a unique group key for the Device Table. Given a recloser ***Code*** and ***Scale***, its corresponding ***Family*** value may be obtained. Utilizing the ***Family*** value, all pairs of curves stored in the Curve Table may be obtained that are associated with the given recloser. The ***Selector*** variable may then be used to choose a particular pair of operating curves.

For relays, there is a many-to-many relationship between rows in the Device Table and rows in the Curve Table. To select a specific relay the ***Code***, ***Style***, tap setting, and time-dial setting must be specified. The relay ***Code*** selects a given class of relay. The ***Style*** variable is unique for each different family of curves. The value for tap settings are stored in the ***Scale*** array variable. The ***Selector*** variable specifies the time-dial setting.

With relays, the variables ***Code***, ***Type***, ***Scale***, and ***Style*** may be used as a unique group key for the Device Table. Given the ***Code***, ***Scale***, and ***Style*** for a relay, its corresponding ***Family*** value may be determined from the Device Table. Having the ***Family*** value, all curves stored in the Curve Table that are associated with the given relay ***Style*** may be obtained. The ***Selector*** variable may then be used to specify a particular curve.

Tables 5.3 and 5.4 summarize information concerning row relationships and keys for the Device and Curve Tables.

It should be noted that the ***Cost*** and ***Main_Cost*** data contained in the Device Table, presented in Table 5.1, contain information that can be used for economic evaluations of protective devices. The ***Failure*** and ***Repair*** data in the Device Table can be used when considering circuit reliability and restoration functions.

Table 5.3. Row Relationships Between Device and Curve Tables

Table	Row Relationships		
	Fuses	Reclosers	Relays
Device	One	One	Many
Curve	One	Many	Many

Table 5.4. Keys for Device and Curve Tables

Table	Keys for Rows and Devices			
	Row Key	Fuse Key	Recloser Key	Relay Key
Device	Device	Code, Type	Code, Type, Scale	Code, Type, Scale, Style
Curve	Curve	Family	Family, Selector	Family, Selector

5.3. Key Features Summary of Relational Protective Device Model

The key features of the relational protective device model are summarized below --

- The model uses two database tables, the Curve and Device Tables, to store the protective device data. Using relational links between these tables the model is able to significantly reduce the amount of required data storage.
- Since the protective device data is compacted it can be loaded into computer memory by DANE, and no hard-disk accesses are required to retrieve this data. Thus, software applications that utilize protective devices execute faster.
- The protective device data storage is centralized and more manageable in a relational database system.
- The writing of database queries is simplified for future work, as illustrated later in Chapter 7 of this report.

CHAPTER 6

Expert System Design

6.1. Introduction

The stated objective of this research is an expert system implementation for protection system design. Expert system applications are considered a subset of Artificial Intelligence [36]. The goal of an expert system is to mimic human expertise in some application. An expert system must be loaded with knowledge or information concerning the subject area. This knowledge forms the knowledge base for the expert system. As more knowledge becomes available it may be used to update and expand the knowledge base.

For a given problem the expert system searches its knowledge base to reach a decision. The most prominent search methods are forward chaining, backward chaining, and rule based searches. Typically, expert systems use a combination of search method techniques [51].

The knowledge base information is usually stored in some form of lists. These lists contain related information or data. The search methods process the information in the relevant lists. Thus, the search does not examine all information in the knowledge base. The search methods and information lists are often grouped together and referred to as the Inference Engine of the expert system. A typical expert system should consist of knowledge bases, search methods, and information lists. A programming language to implement an expert system must facilitate these basic requirements.

In order to accomplish an integrated approach for protection system design, basic data, or knowledge, must be used to create more knowledge. The basic knowledge is referred as static data, and the created knowledge is referred to as dynamic data. Expert knowledge is incorporated into the protection system design knowledge base via implemented rules.

The static data can be stored in a database. Examples of static data include line data, transformer data, and time current characteristic curves for protective devices. Using static data, the protection system design software performs calculations which create dynamic data about the distribution system.

The circuit data is fundamental to other protection system design software. Distribution circuits are constructed using various individual components such as lines, switches, and transformers. These individual components are referred to as parts. Static parts data are used in modeling the physical circuit. The topology for the system of circuits is defined by the user. The circuit data must be created by some process that relates circuit topology and static parts data. Figure 6.1 indicates how the static parts data and circuit topology are processed to create dynamic circuit data.

The overall protection system design problem may be decomposed into four subproblems or functions. Each function creates new information for the knowledge base. The four functions are fault analysis, coordination, placement, and selection. Figure 6.2 illustrates these functions.

Fault analysis uses dynamic circuit data to produce dynamic fault analysis data. Coordination uses static protective device data and rules pertaining to device coordination to produce dynamic coordination data. Using rules about placement of devices, dynamic fault analysis data, and dynamic circuit data, placement calculates dynamic placement data. Selection processes dynamic circuit, coordination and placement data using rules about protective device selection to produce coordinated protective devices. This integration of the data flow produces a rule-based coordinated protection system design.

Figure 6.3 shows the flow of the created data and interactions among the four functions. Each function produces new knowledge that is based on existing data. The created knowledge is also be dependent on user decisions. The user develops the circuit

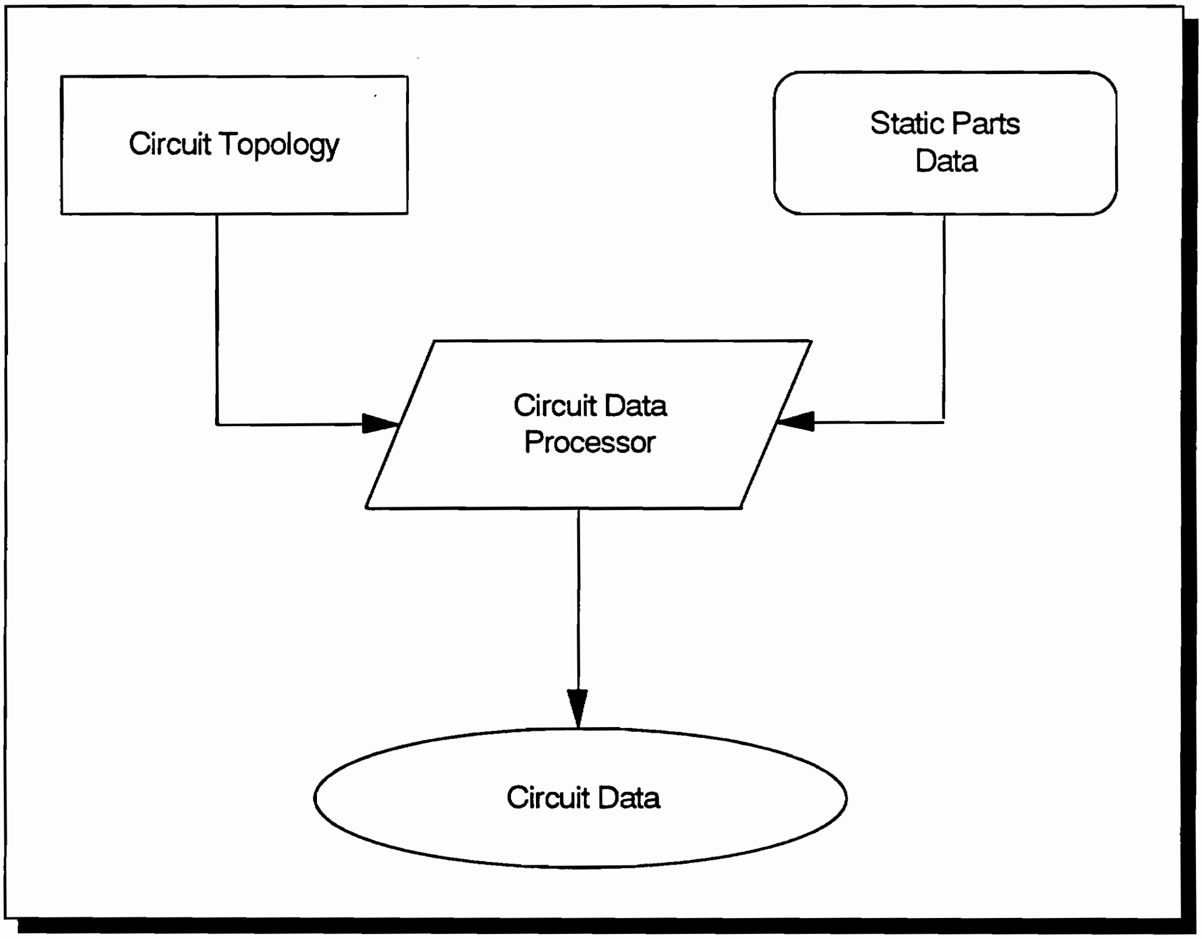

Figure 6.1. Creation of Circuit Data

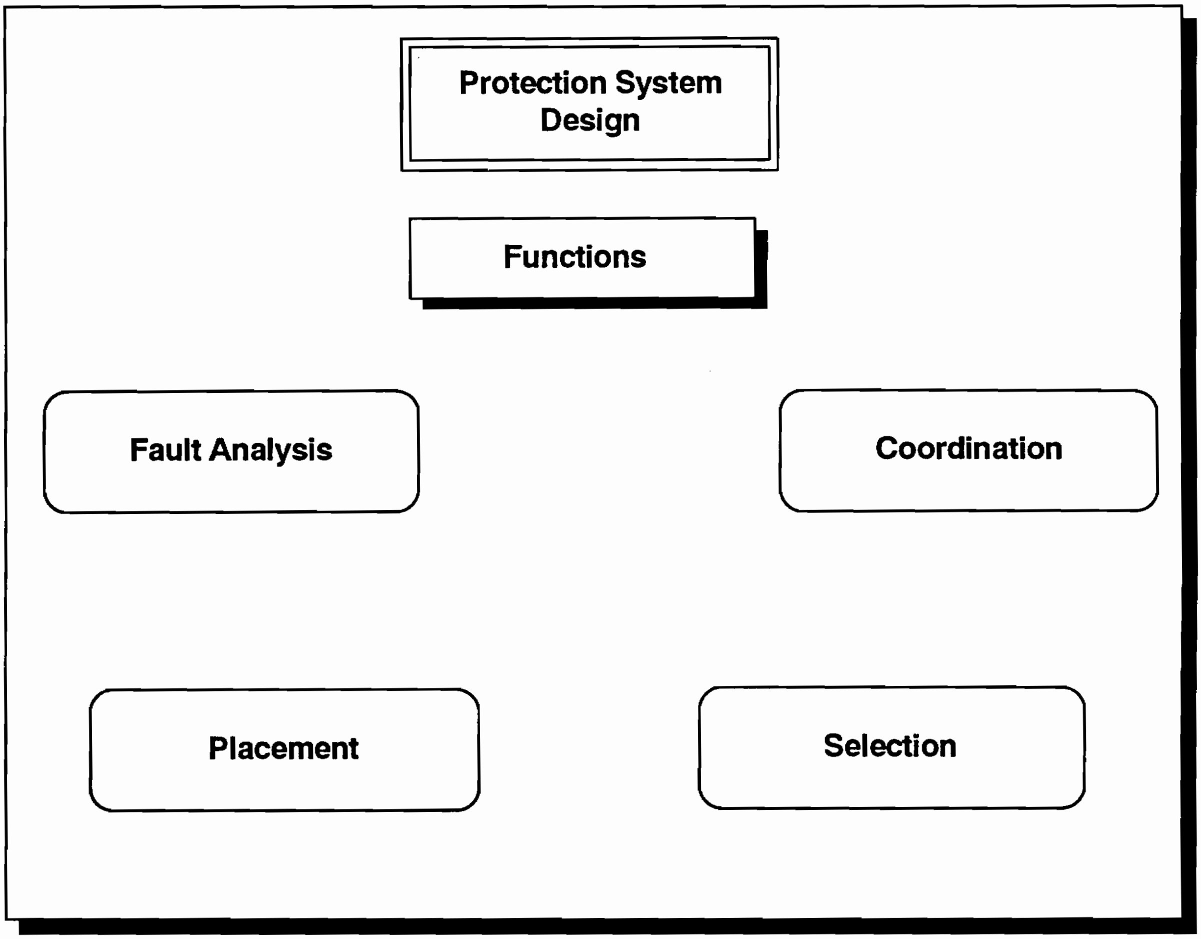

Figure 6.2. Protection System Design Functions

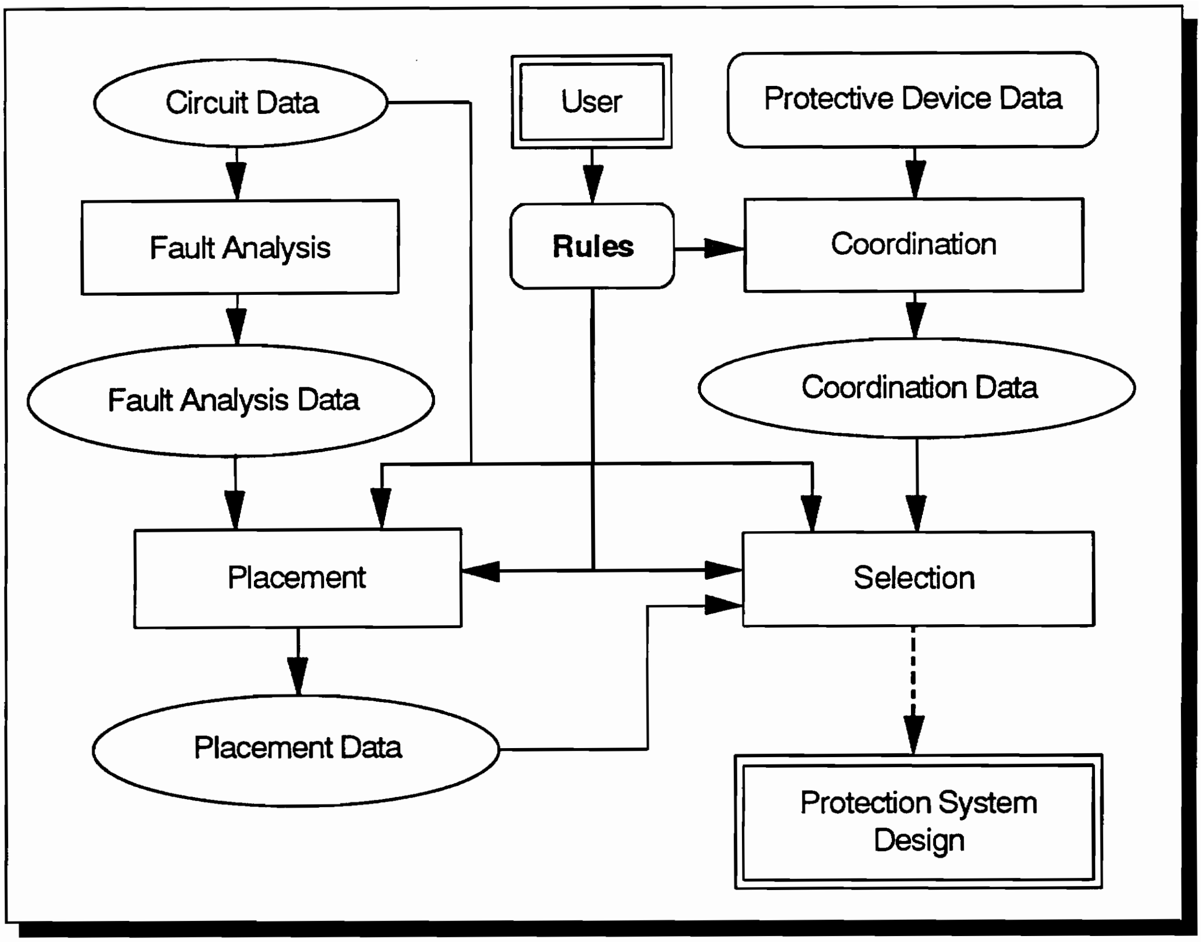

Figure 6.3. Created Data Flow and Interactions Among Functions

model representations for the system of physical circuits. The user controls variable rules that influence the coordination, placement, and selection functions. The protection system design knowledge base consists of both static and dynamic data, where the dynamic data is influenced by user decisions.

During the initial phases of this research alternative programming language platform developments were considered for the expert system. The process evaluated two routes for the development. One platform involved the Prolog environment, and the other platform considered a combination of the C and Embedded Structure Query Language (ESQL) languages. The evaluation process is presented in the next section.

6.2. Evaluation of Prolog Versus C/ESQL Language Platforms

Both Prolog and C/ESQL programming languages are capable of supporting expert system development. However, the languages tend to be at opposite ends of the programming language spectrum. Prolog is a declarative language that tells the computer WHAT task to perform while C is a procedural language that tells the computer HOW to perform the task [36].

A crucial factor in the implementation of an expert system is the application criteria. The application of the expert system for this research involves protection system design for electrical distribution systems. Therefore, the evaluation process encompasses aspects pertaining to protection system design.

Three metrics considered during the evaluation of the suitability for a programming language to implement the expert protection system design are as follows:

1) Knowledge Base Capabilities,
2) Search Methods, and
3) Information Lists.

The decision regarding which programming language platform to use for the implementation is based on the evaluation of these three metrics.

Knowledge Base Evaluation: A relational database system is used in protection system design for efficient storage and manipulation of data. Prolog supports relational databases. C/ESQL also supports relational databases. However, the knowledge base for the protection system design application is incomplete. As such the programming language implementation must support arithmetic calculations to complete the knowledge base. Prolog was not designed with the intent of supporting arithmetic calculations.

Inference Engine Evaluation: Search Methods and Information Lists are combined and referred to as the Inference Engine. The combination of ESQL and C provides two operating modes for the inference engine. Linked lists of data structures are formed using pointers in C. The information in these data structures is processed, or searched, in order to implement expert rule-based requirements. Pointers in C serve a dual function, the formation of information in linked lists and also searching through the information in the linked lists. C provides what is referred to here as a procedural operating mode for the inference engine. The fault analysis, placement and coordination functions can be implemented using a procedural type inference mode.

ESQL is a declarative language which, much like Prolog, tells the computer WHAT task to perform. The declarative code necessary to perform a complex task is very simple. ESQL can be used to implement rule-based expert systems [39]. By querying the database, ESQL can retrieve data that satisfy rule requirements. The ESQL provide what is referred to here as a declarative operating mode for the inference engine. The declarative inference operating mode, using ESQL, can efficiently facilitate complex device selection logic.

Both Prolog and the combination of C/ESQL provide good inference engine support. Prolog's declarative statements provide excellent inference engine capabilities that are easily implemented, provided the knowledge base is complete.

6.2.1. Evaluation Conclusions

Expert systems applications with complete knowledge bases are implemented using Prolog, but far more computer users are familiar with C [36]. The expert system application for protection system design requires dynamic knowledge creation that is heavily dependent on arithmetic calculations. These arithmetic calculations are more easily implemented using C as opposed to using Prolog. The implementation of the arithmetic calculations for the protection system design application is more complicated with Prolog then with C/ESQL.

The expert system implementation could use a combination of C and Prolog. The arithmetic calculations could be handled by C coded functions, and the inference engine could be coded using Prolog. However, the mixing of two programming languages is complex and creates problems [36], and the problems created by mixing two programming languages can be avoided in this research application. Using C/ESQL the inference engine can be effectively implemented with two modes of operation. The execution speed of C/ESQL will be faster than a Prolog version [38].

The evaluation of the three metrics - knowledge base, search methods and information - for the protection system design application has demonstrated the difficulties involved in using a Prolog expert system implementation. Thus, the final expert system for protection system design has been implemented using C and ESQL.

Figure 6.4 shows the final expert system design using C/ESQL as the development platform. Figure 6.4 depicts the static and dynamic data parts of the knowledge base. Inference modes and rules use knowledge from the static data together with knowledge form the dynamic data to create more dynamic data for the knowledge base. Inference modes use

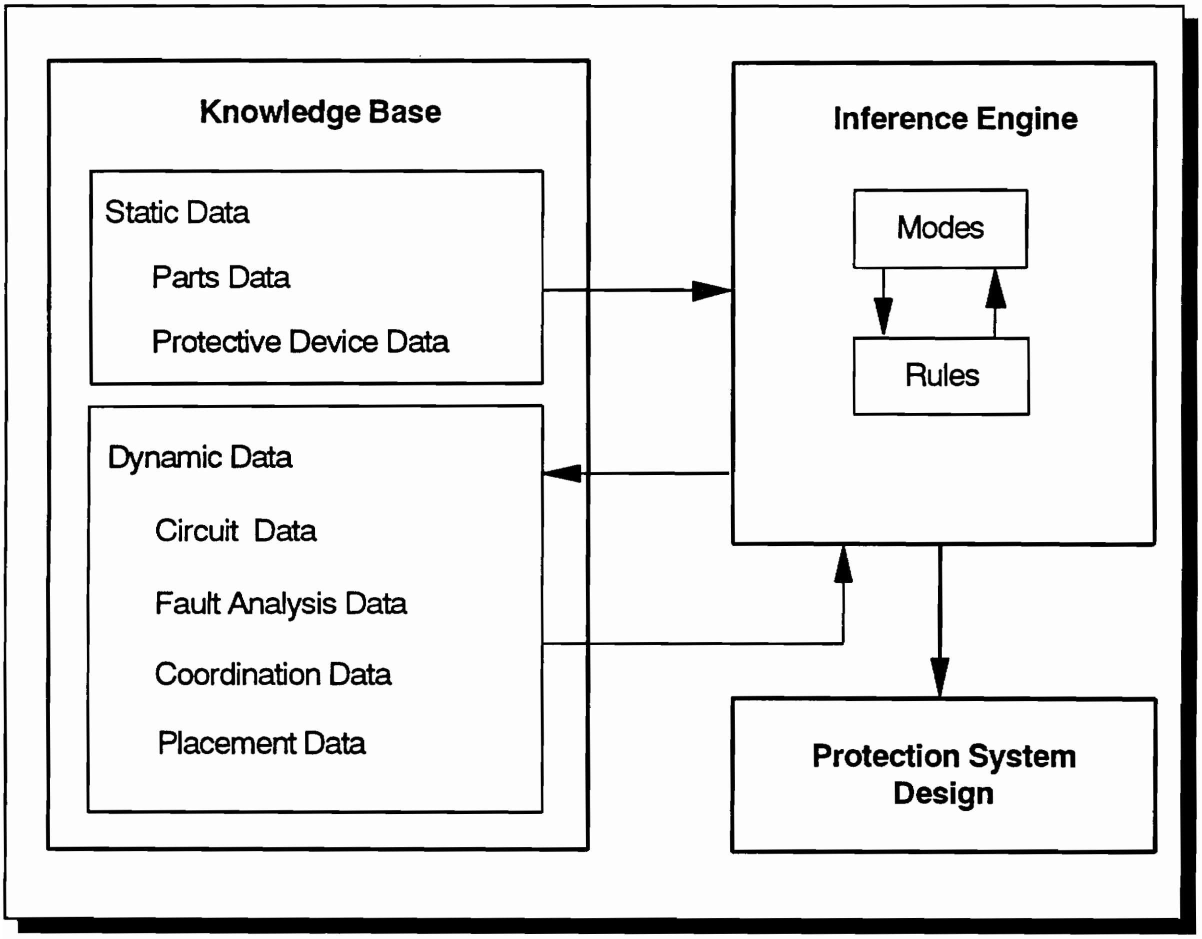

Figure 6.4. Final Expert System Design

both C and ESQL capabilities. The C language uses lists of data structures, or information lists, with pointers to created linked lists that functions may rely on to provide procedural inference by pointer manipulation. The ESQL implements declarative inference using SQL Select Statements. The rule-based expert system inference engine has two operating modes, procedural and declarative. The procedural inference mode is used to create new knowledge while the declarative inference mode is used on existing knowledge.

The remaining sections of this chapter present specific topics related to the functional components that create the expert system for protection system design. The expert system is implemented in the DANE workstation environment. DANE provides many key features that are necessary for the expert system development. DANE provides a relational database management system, manages complicated data and topological relationships using pointers, and provides a graphical user interface (GUI).

6.3. Dynamic Data Creation

The data associated with a system of interconnected distribution circuits can often be overwhelming for the protection system design engineer. Vast quantities of data must be manipulated and interchanged by the engineer. As noted previously in Chapter 4 of this report, whenever the configuration for a system of interconnected circuits changes the values from fault analysis will also change. Additionally, on tie-line components the flow of current may reverse during changes in configurations.

The circuit data, as referred to in this report, includes both the configuration and component types for a circuit For distribution circuits this data is rarely stable and more often than not in a state of flux due to various factors -- such as circuit reconfigurations, circuit expansion, or circuit construction modifications. Thus, circuit data is dynamic in nature. The Circuit Data Processor shown in Figure 6.1 is implemented by the core of DANE. The dynamic circuit data is managed for application users by DANE. As illustrated in Figure 6.5, functions in DANE are provided access to circuit topology as well as access to the parts data that is associated with the circuit components. This data is contained in Component objects as discussed in Chapter 4 of this report. Workstation applications can process circuit topology or utilize parts data in calculations using the available pointers provided by DANE. These pointers are managed by DANE. The pointers which define the topology are reset by DANE whenever the circuit configurations change. The pointers associated with the type of component only change if a component is replaced in the circuit.

Fault analysis utilizes this feature in DANE during circuit reconfigurations to determine tie-line data. For interconnected circuits this is a key feature -- the ability to establish and determine the magnitudes of bi-directional fault current flows. The pertinent data is integrated by fault analysis and used by other protection system design functions. For example, the placement of protective devices by the Placement function is determined from the fault analysis data and user implemented control rules.

The relationship between fault and load currents is another key issue during the design of a protection system. If the load current flow through a component is greater than the minimum fault current then a fuse type device cannot be used for protection at that location. For each circuit configuration examined by fault analysis a load flow analysis is also performed. This procedure is used to develop a maximum load current flow through a circuit component based on all configurations that have been analyzed by the design study.

6.4. Influencing Design Rules

The developed rules that apply to the three functions for the expert system are presented in this section. Protection system designers apply rules to the coordination, placement, and selection of protective devices. Figure 6.6 shows those functions which have rules that influence their decisions. As illustrated in Figure 6.6 the user controls the rules

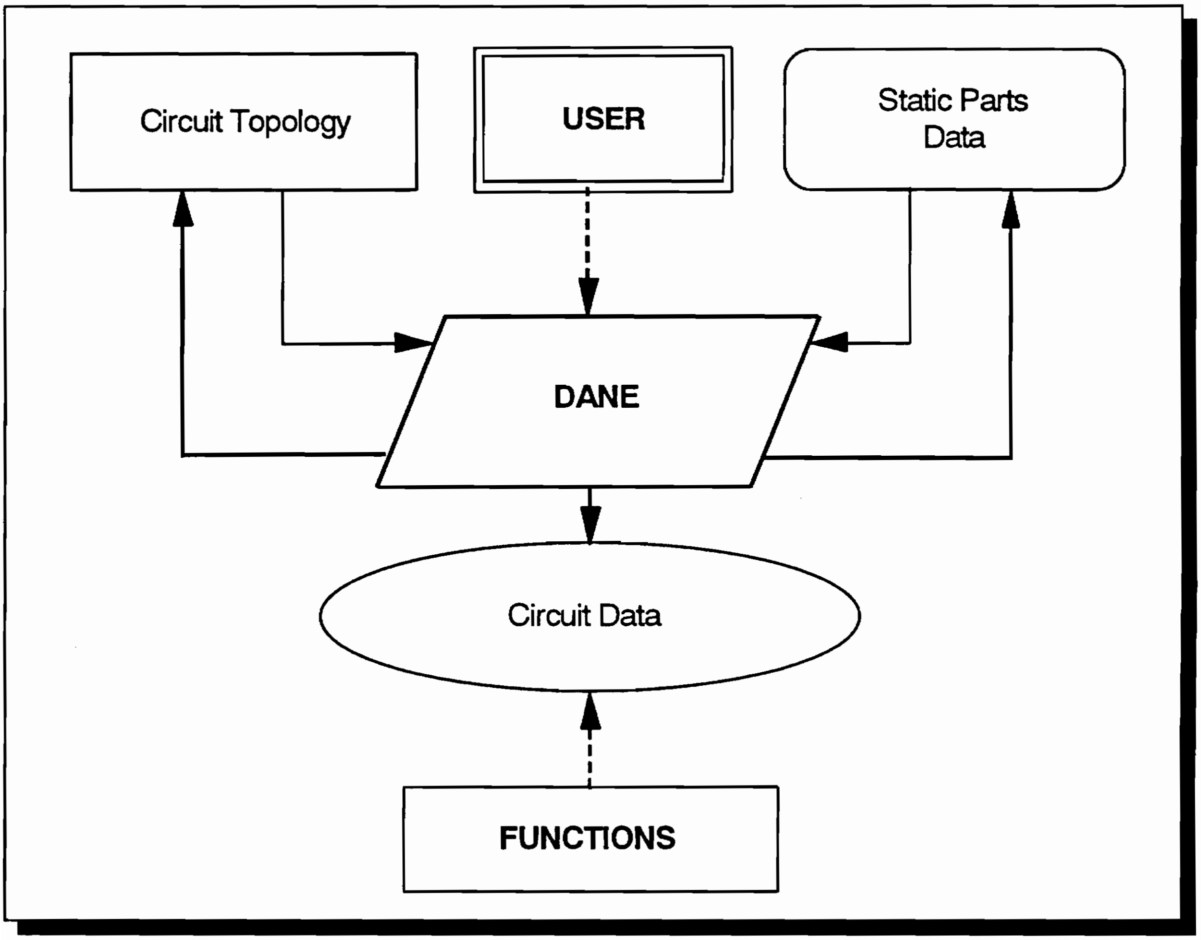

Figure 6.5. Dynamic Circuit Data Interface Using DANE

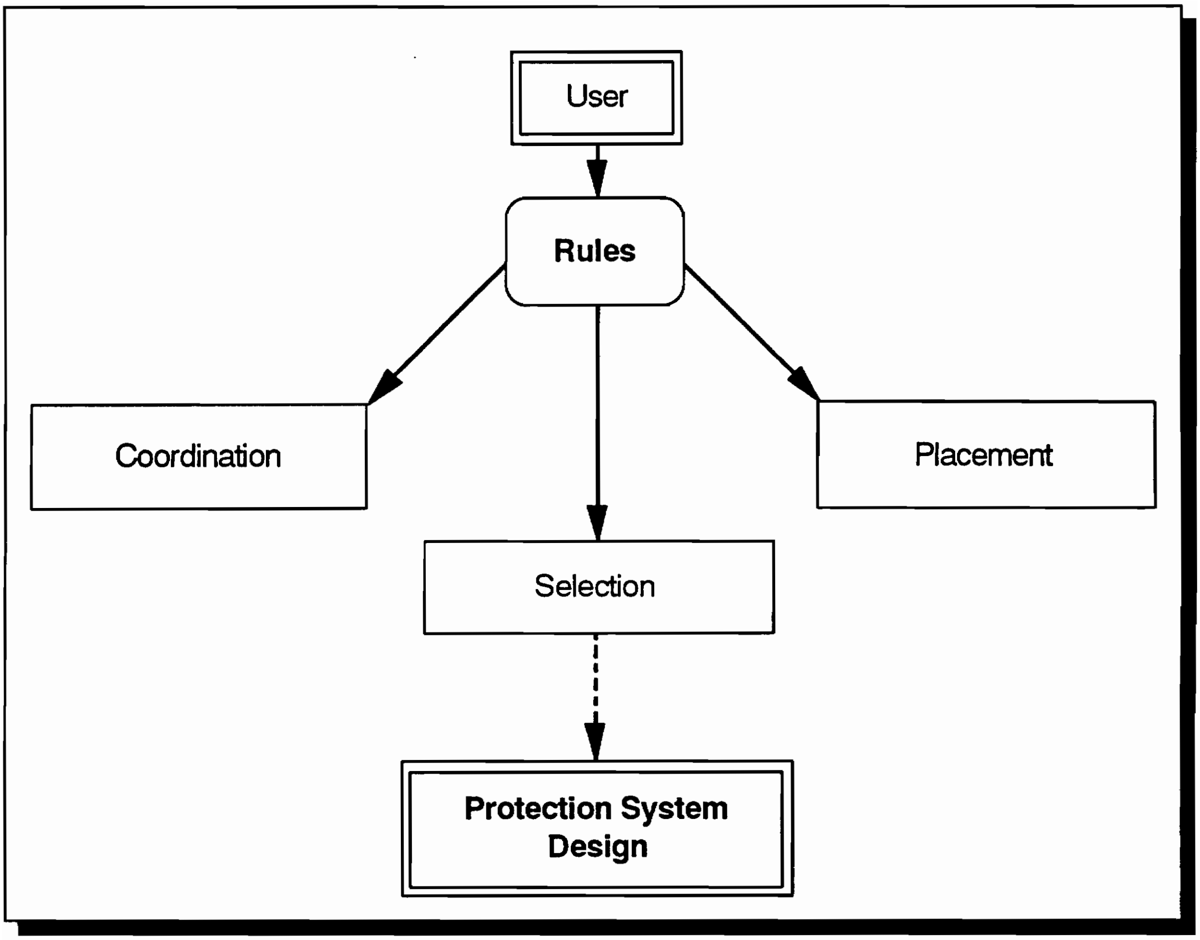

Figure 6.6. Inference Engine Functions With Applied Design Rules

associated with these functions. To determine whether or not a rule is to be considered, the inference engine processes user defined logic variables, and any of the associated rules that are described may be turned on or off by the user. Some of the rules also have associated parameter values.

6.4.1. Coordination Design Rules

Basic design philosophy is that the protective device closest to a permanent fault should operate to clear the fault before any upstream protective devices operate to clear the fault and before any damage is inflicted on upstream devices. However, if the closest protective device fails to clear the fault within a given time period, the next upstream device should be capable of sensing and clearing the fault. The device closest to the fault is referred to as the primary device, and the upstream device is referred to as the backup device. In a case where the next upstream device cannot sense the minimum fault current, then a recloser ground trip is used as backup protection.

Table 6.1 presents the rules for coordination in terms of the primary device curve, the backup device curve, and the coordination parameter. The fault type is indicated with a "P" for Permanent fault and a "M" for Momentary fault. An additional coordination rule that is applied which does not appear in Table 6.1 is as follows:

Rule ***C13*** = *Devices are considered to coordinate only if the current range over which they coordinate execeeds a user defined parameter.*

Note that typical coordination parameter values are given in Table 6.1. The designer sets the coordination parameter value associated with every rule that is implemented in Table 6.1. The coordination parameter applies to the minimum time distance between the primary and backup curves for the current range over which the curves coordinate. The value of the coordination parameter effects both the range of fault amperes over which a device pair coordinate and the number of device pairs that coordinate.

Table 6.1. Coordination Rules

Rule Label	Fault Type	Primary Curve	Backup Curve	Parameter
C1	P	Fuse Clearing	Fuse Melting	75%
C2	M	Fuse Melting	Fast Recloser Trip	75%
C3	P	Fuse Clearing	Delayed Recloser Trip	95%
C4	P	Fuse Clearing	Relay Trip	95%
C5	P	Delayed Recloser Trip	Fuse Melting	75%
C6	M	Fast Recloser Trip	Fast Recloser Trip	95%
C7	P	Delayed Recloser Trip	Delayed Recloser Trip	60%
C8	P	Delayed Recloser Trip	Relay Trip	95%
C9	P	Relay Trip	Fuse Melting	75%
C10	P	Relay Trip	Fast Recloser Trip	95%
C11	P	Relay Trip	Delayed Recloser Trip	90%
C12	P	Relay Trip	Relay Trip	90%

The intent of the coordination parameter is to provide some safety margin between device pair coordination and also model the time delay of operations in certain devices. For instance, note the typical coordination parameter given for rule ***C7*** is 60%. The intent is to model the time delay involved with delayed recloser trip curve operations.

The effects of varying the coordination parameter value is illustrated by the example presented in Figure 6.7 which involves the coordination of two fuses as controlled by rule ***C1***. Figure 6.7 graphically demonstrates the effects as the value of the coordination parameter is changed from 80% to 60%. The range of fault amperes over which the two fuses coordinate decreases from about 1025 to 350 amperes as the coordination parameter is decreased from 80% to 60%, respectively. If the parameter value associated with rule ***C13*** was set at 400, the two fuses would not be considered as coordinating, when the coordination parameter value is set at 60% for rule ***C1***. Thus, the value of the coordination parameter associated with each implemented coordination rule has a profound impact device coordination.

The Coordination Rules are processed by the Coordination function of the Inference Engine. The Coordination function processes the designer implemented Coordination Rules and builds a table of coordinated primary and backup protective device pairs. The Coordination Rule Processor is described in Section 6.7.1 of this report, during the discussion of the Inference Engine.

6.4.2. Placement Design Rules

Placement design rules are used to establish protection zones on the system of distribution circuits. At the distribution level, zones of protection are not easily identified by any standard procedure. This is due in large part to the dynamics of the customer loading on the system. The establishment of the protection zones is dependent almost exclusively to designer decisions. In this research, the placement design rules reflect common practice

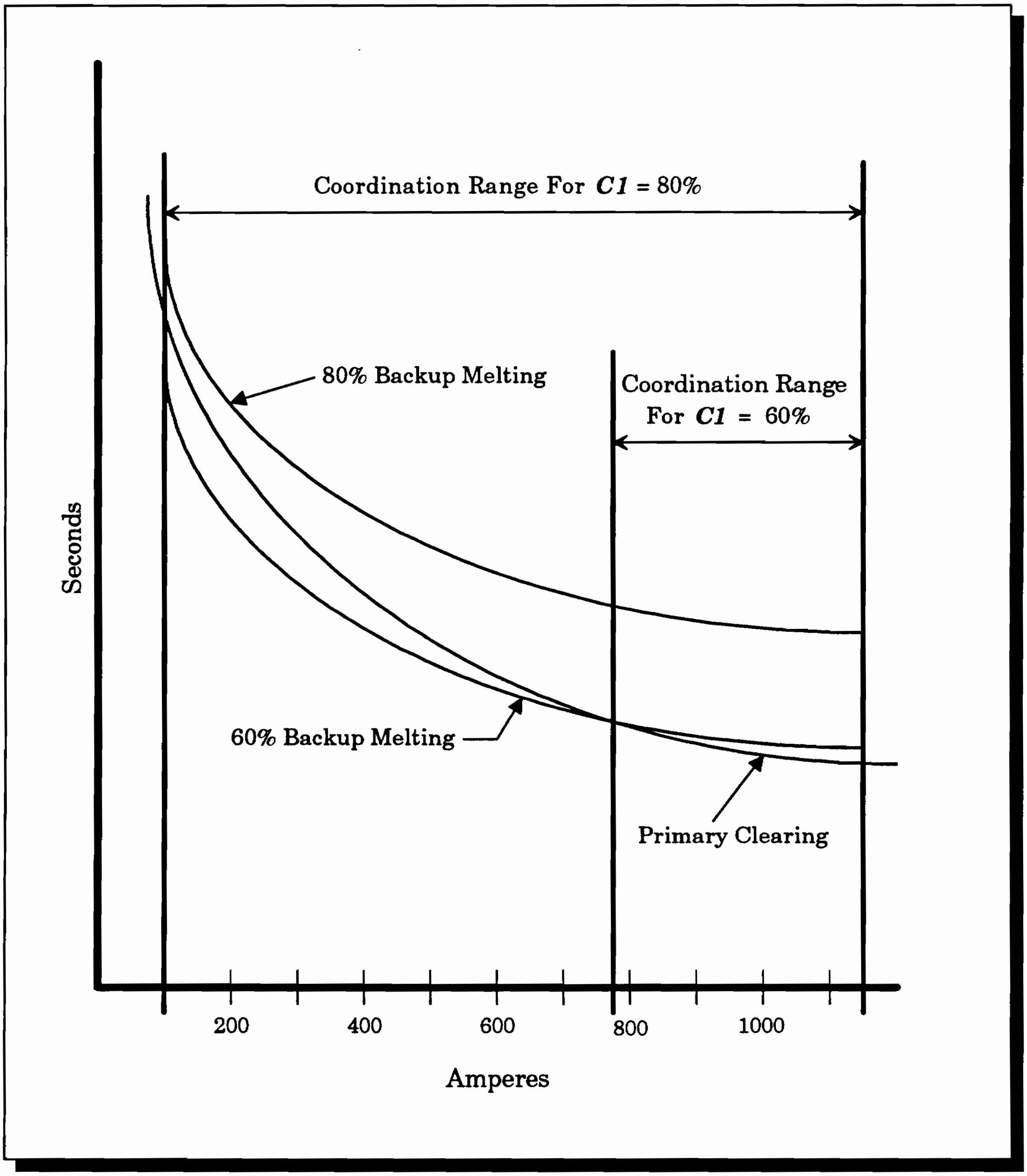

Figure 6.7. Effects of Coordination Parameter Value on Device Pair Coordination

among protection system design engineers in this decision making process. The placement design rules implemented in this research in no way represent an inclusive set of common practices among protection engineers. They do however represent some of the prevalent rules concerning the placement of protective devices.

Table 6.2 presents the placement rules implemented by the expert system. In the rule descriptions, terms used in Table 6.2 are defined as follows:

device zone = *that portion of the circuit in which if a fault occurs the device is the first line of defense .*

tie-line = *a section of feeder in which the flow of current may reverse due to switching operations.*

The placement rules fall into two categories. For the first category, the rules are inflexible and user specified parameters do not exist. Specific examples of this first category are placement design rules ***P1***, ***P2***, and ***P3*** as shown in Table 6.2. In the second category user specified parameters exist which influence the placement of devices and consist of the remaining placement rules ***P4***, ***P5***, ***P6***, ***P7***, and ***P8***.

The application of placement rules may depend upon having results from engineering analysis functions. If a rule needs data from an engineering analysis function, then the function that is needed is indicated at the end of the rule description in Table 6.2.

All of the designer activated Placement Rules are processed by the Placement function of the Inference Engine. The Placement function processes the Placement Rules to evaluate circuit locations for the establishment of new protection zones. For such an evaluation at a given location, the potential new zone will depend upon previous downstream placements of devices. The Placement Rule processor is described in Section 6.7.2 of this report, during the discussion of the Inference Engine.

Table 6.2. Placement Rules

Rule Label	Parameter	Rule Description & Engineering Analysis Functions
P1	No	A device is located at the start of each circuit.
P2	No	Devices are located at both the primary and secondary sides of all transformers.
P3	No	Placement of devices back-to-back is not allowed. For a pair of devices placed back-to-back, if one of the devices has been placed by the user, then the other device is removed. Otherwise, the upstream device is removed.
P4	Yes	If the total length of the downstream lateral exceeds the user defined parameter, then a device is located at the start of that lateral.
P5	Yes	If the ratio of the maximum fault current to the minimum fault current for a potential new zone exceeds the user defined parameter, then a device is placed at the circuit location being evaluated. (*Fault Analysis*)
P6	Yes	If the number of customers in a potential new zone exceeds the user defined parameter, then a device is placed at the circuit location being evaluated. (*Customer Information System Analysis*)
P7	Yes	If the failure rate of a potential new zone exceeds the user defined parameter, then a device is placed at the circuit location being evaluated. (*Reliability Analysis*)
P8	Yes	For a feeder tie-line, the number of devices to be evenly distributed over the length of the tie-line is equal to the length of the tie-line divided by the user defined parameter.

6.4.3. Selection Design Rules

Once the location of protective devices have been specified, devices that will protect and coordinate for all envisioned faults must be selected. Selection Design Rules are used to control this decision making process. The Selection Design Rules implemented by the expert system are based on standard procedures involved with protection system design. Table 6.3 presents the selection rules applied by the expert system. In the rule descriptions, terms used in Table 6.3 are defined as follows:

pickup = *minimum fault current which a device will sense and protect against.*

device backup zone = *that portion of a circuit for which a protective device is the second line of defense.*

However, the implemented rules, presented in Table 6.3, are not intended to represent any standardized set of operating guidelines or practices concerning the area of protection system design. The purpose for most of the implemented Selection Design Rules is quite obvious to a protection system design engineer. For instance, Selection Design Rule *S2* indicates that any protective to be selected at a given location must be capable of operating at the system voltage level at that location. The other more obvious Selection Design Rule is *S7* which to summarize simply indicates that if a given device type will not coordinate then attempt coordination using another device type until all device types have been examined.

The Selection Design Rules also fall into the same two categories as Placement Design Rules, which are rules without parameters and rules with user specified parameters. The Selection Design Rules without parameters, i.e. *S1 - S8*, impose fundamental constraints on those protective devices that are to be selected, and the constraints force the selected protective device to meet certain basic requirements. The basic requirement are based on data involved with the protection system design.

The remaining Selection Design Rules are intended to provide for some flexible and design preferences during the selection process. For example, all utilities do not use a relay controlled breaker at the start of the circuit in the substation; some prefer a recloser instead. Rule ***S10*** incorporates this knowledge with its implementation and provides the flexible to allow the designer to make this choice. The other Selection Design Rules with parameters allow the designer to provide for some safety margin in the design. The parameters are used to scale certain values to insure that the protective device will operate properly. For example Rule ***S12*** permits the designer to multiple, or scale, the peak load current through a protective device by the value of the parameter. This parameter is used to reflect a load growth factor on the circuit. The scaling factor insures the designer that the selected device will be able to operate without damage, as long as the load current does not exceed the expected load growth factor specified by the parameter associated with Rule ***S12*** .

The application of selection rules may depend upon having results from engineering analysis functions. For example, feeder tie-lines must be switched and analyzed for different circuit configurations to insure proper tie-line protective device selection and operation. The engineering analysis of the different circuit configurations are implemented using the reconfiguration function [50]. If a rule needs data from an engineering analysis function, then the function that is needed is indicated at the end of the rule description.

The activated Selection Design Rules are processed by the Selection function. The Selection function is the final processing step in the design of the protection system and is dependent on data from several sources and other functions. The Selection Rule processor is described in Section 6.7.3 of this report, during the discussion of the Inference Engine.

Table 6.3. Selection Rules

Rule Label	Parameter	Rule Description & Engineering Analysis Functions
S1	No	For a set of devices, which satisfies all constraints, the device is first selected based upon having the smallest continuous current rating and then is selected based upon being the fastest operating device. An exception to this rule occurs when a device is being selected at the end of a branch. In this situation the device DOES NOT serve as backup for any other protective device. The device, which is typically a fuse, is selected as LARGE as possible to detect the minimum fault current in its protection zone.
S2	No	The voltage rating of the circuit must fall within the operating voltage range for the protective device.
S3	No	Unless at the start of a circuit or if there are downstream fuses, then reclosers are selected at three-phase locations.
S4	No	The pickup of a device must be less than the minimum of the primary and backup zone fault currents. For a tie-line, this rule applies to both directions. (*Fault and Reconfiguration Analysis*)
S5	No	The pickup of a device must be less than the minimum of the equipment damage curves over the actual fault current range. For a tie-line, this rule applies to both directions. (*Equipment Rating and Reconfiguration Analysis*)
S6	No	The fast trip curve of the first recloser selected must coordinate to the end of the circuit.
S7	No	If a fuse is being selected and coordination fails, then select a recloser; if coordination fails using recloser selection, then select a relay.
S8	No	Use a ground trip if coordination cannot be achieved for minimum downstream currents, and also when the user defined parameter for ***S9*** times peak load current exceeds minimum fault current .
S9	Yes	The pickup of a device must be greater than the user defined parameter times cold load inrush or peak load current at the given circuit location. For a tie-line, this rule applies to both directions. (*Power Flow and Reconfiguration Analysis*)
S10	Yes	Depending upon the user defined parameter, either a relay or a recloser is selected at the start of the circuit.

Table 6.3. (cont'd) Selection Rules

Rule Label	Parameter	Rule Description & Engineering Analysis Functions
S11	Yes	If a relay or recloser does not need to be selected, then select a fuse until the number of fuses in series in a feeder path trace[47] exceeds the user defined parameter, then select a recloser.
S12	Yes	The continuous current rating of a device must be equal to the user defined parameter times the peak load current at the given circuit location. For a tie-line, this rule applies to both directions. (*Power Flow and Reconfiguration Analysis*)
S13	Yes	The interrupting rating of the device must be greater than or equal to the user defined parameter times the sum of the maximum primary zone fault current and the peak load current. For a tie-line, this rule applies to both directions. (*Power Flow, Fault, and Reconfiguration Analysis*)

6.5. Knowledge Base

The knowledge base contains both the data and protection system rules that can be implemented by the designer as shown in Figure 6.4. A large portion of the knowledge base for the expert system is contained within the relational database of DANE. One type of data contained in the knowledge base is referred to as Static data. The Static data consists of the Parts data and Protective Device data. The Parts data represent tables that contain information about equipment that is used to build distribution circuits such as line conductors, transformers, and switches. The Device and Curve tables discussed in Chapter 4 are examples of Protective Device Data. All of the Static data is stored in relational database tables. The most distinguishable feature regarding the Static data is its relative stability.

The other data type contained in the knowledge base is referred to as Dynamic data. The reference to Dynamic data is attributably to the characteristic of this data type to change based upon information from other sources. Dynamic data in most instances is derived from Parts data, but the most critical factor in the determination of the dynamic data is due to the influence of other controlling factors. For example consider two cases involving a tie-line section of circuit that consists of three parts: a line conductor, a switch and another line conductor. For case one presented in Figure 6.8.a, the configuration of the circuit is such that all of the tie-line components are fed by a single substation. In Figure 6.8.b the switch, *SW 1*, is opened, and the tie-line component of *Line 2* is fed from another substation. The data results from Fault Analysis will be vastly different between the two cases illustrated in Figures 6.8.a and 6.8.b. The most obvious being that the current flow has reversed on *Line 2* after *SW 1* is opened in Figure 6.8.b. For the example given the Static data remains fixed; yet the impact of information regarding the circuit configuration has a profound impact on the fault analysis data.

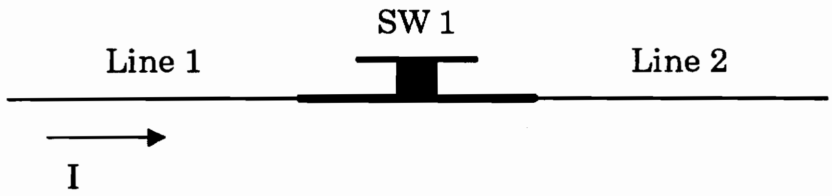

Figure 6.8.a. Three Component Tie-Line Section With SW1 Closed

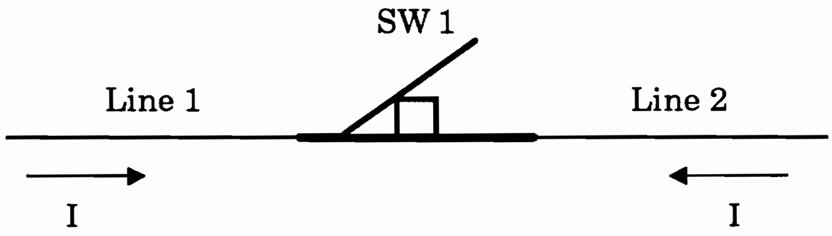

Figure 6.8.b. Three Component Tie-Line Section With SW1 Opened

Dynamic data consists of circuit configuration data, GUI input data for the inference engine, and data created by the inference engine. Figure 6.9 presents a tree structure of information stored in the knowledge base of the relational database.

Circuit configuration data is stored in the switching configuration table of the database. Two methods are available to create circuit configuration data. One method allows the designer to arbitrarily specify the switching patterns of the interconnected circuits that are to be considered during the design of the protection system. The second method allows a reconfiguration function to specifies the switching configurations of the interconnected circuits, that are derived from improved efficiency among various loading conditions [50]. Each configuration of circuits, that is based on the switching configurations table, must be considered by the integrated protection design system. An example of a typical switching configurations patterns is given by Table 4.3.

The GUI interface is used to build, modify, and store circuit data. The GUI input data for the inference engine consists of engineering analysis parameters, rule parameters, circuit data, and rules to apply. The engineering analysis parameters affect the results of the engineering functions that provide data used by the placement and selection processes. Such parameters include load growth assumptions that affect power flow results and impedance values to be used for non-bolted fault calculations, i.e. ***ZtoG*** as defined in Chapter 4, Section 4.3.2. The rule parameters associated with the coordination, placement, and selection rule processors are given in Section 6.3. The designer utilizes the GUI to store decisions concerning which rules are to be applied by the inference engine. The discussion of the inference engine functions is presented in Section 6.7.

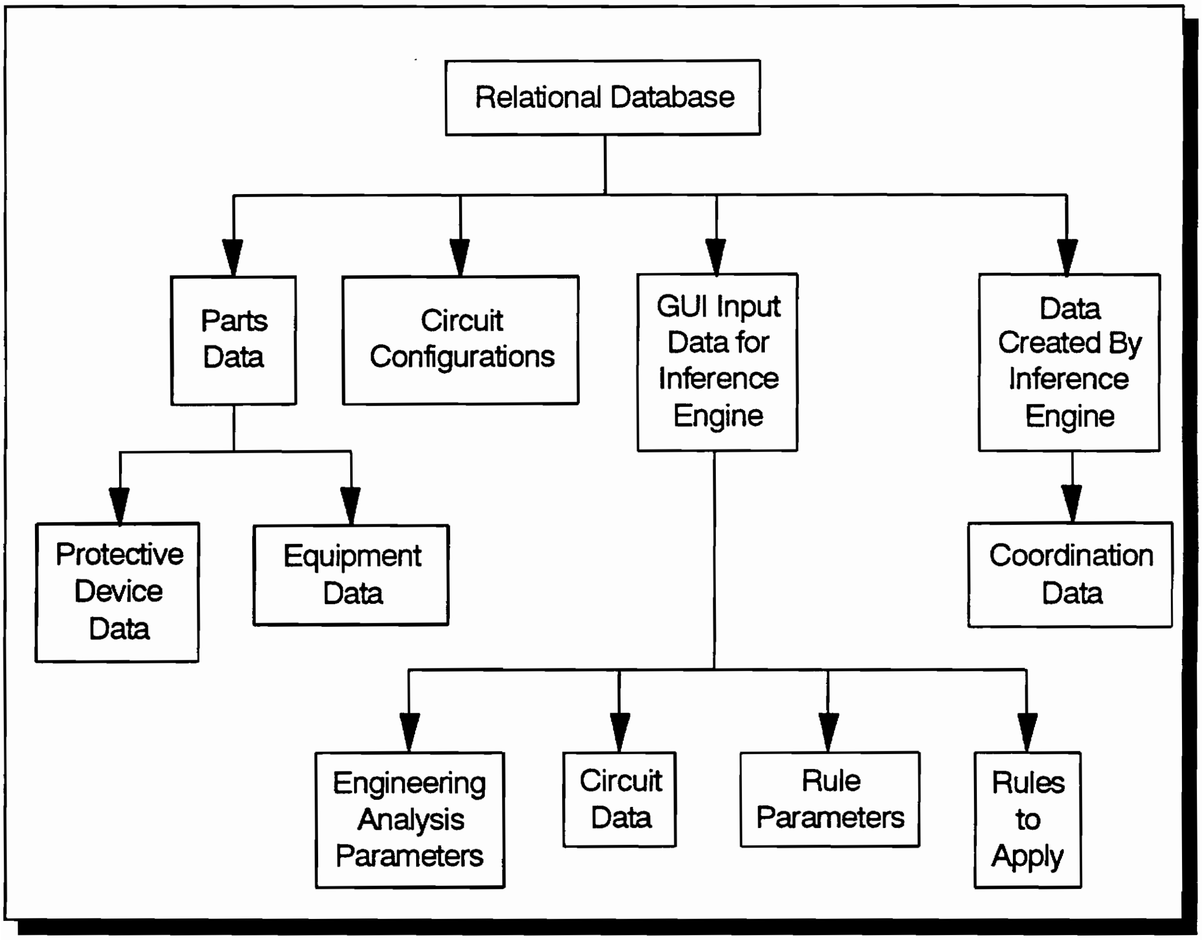

Figure 6.9. Tree Structure of Information Stored in Relational Database

6.6. Sharing Of Data Among Functions

Data is shared among functions using objects. Two types of shared objects are Part and Analysis objects which are linked to a Component object via pointers. Data within the Part and Analysis objects is accessed using the appropriate pointer contained in the Component object.

The most common type of object is the Part object. An example of a Part object is a protective device. The data associated with a protective device is contained in two separate Part objects that are linked via pointers to a component object. The pointers contained in these protective device component objects are used to access the required data.

The other type of object is an Analysis object. Analysis objects are created by functions and attached to component objects using data from Part objects. For instance, the fault analysis function relies on Part objects to create a data object of results that is linked to every component that is processed. The Placement function utilizes Fault Analysis objects and Part objects to create Placement objects. Thus, Analysis objects are created using both Part and existing Analysis objects.

6.6.1 Accessing Part Objects Data

A data structure defined according to the columns of the Device Table is used to create a Part object in memory of type protective device. The entire Device Table is implemented in memory as a linked list of type protective device Part objects. The linked list is ordered according to Device number. Similarly, the Curve Table is also implemented in memory as a linked list of type protective curve Part objects, and ordered according to Curve number.

If a component is a protective device then it will two Part objects, which are the Device and Curve objects, attached to the Component object that is defined as ***pCmp***. Device and Curve objects are attached to a Component object using the value of the *Device_Offset* and *Curve_Offset* from the Device and Curve tables, respectively. Specific ***Device*** and ***Curve*** objects stored in ***pCmp*** can be accessed using pointer operations to this information as shown by

$$\boldsymbol{pCmp}\text{->}Device\_Offset_i = \boldsymbol{Device} \qquad [6.1]$$

$$\boldsymbol{pCmp}\text{->}Curve\_Offset_i = \boldsymbol{Curve} \qquad [6.2]$$

where C language notation "->" is used for the member access operator for protective device *i* and Table 6.4 contains definitions for the symbols.

The device Part object contains information such as the interrupting rating for a device. To obtain the interrupting rating for a device, the starting pointer to the device part object, ***Sptr_Device***, is used in conjunction with the device number, *Device_offset*, stored in the Component object, ***pCmp***. The protective device interrupting rating, ***interrupt***, is obtained by

$$(\boldsymbol{Sptr\_Device} + (\boldsymbol{pCmp}\text{->}Device\_Offset_i))\text{->}interrupt\ . \qquad [6.3]$$

Similarly, the ijth point of the time current characteristic curve, *CT[i, j]*, for the device may be obtained by

$$(\boldsymbol{Sptr\_Curve} + (\boldsymbol{pCmp}\text{->}Curve\_Offset_i))\text{->}CT[i,j]\ . \qquad [6.4]$$

Table 6.4. Chapter 6 Symbol Definitions

Symbol	Definition of Symbol
Ci	A logic variable that represents coordination rule *i*, *i* = 1, 2,... .
Pi	A logic variable that represents placement rule *i*, *i* = 1, 2,... .
Si	A logic variable that represents selection rule *i*, *i* = 1, 2,... .
L	Logic flag used during the evaluation of designer implemented rules.
Curve_Offset$_i$	A data structure member of the component object which is used in conjunction with the pointer to the Curve portion of the protective device Parts object. It is associated with each protective device component *i* , *i* = 1, 2, 3 ... .
Device_Offset$_i$	A data structure member of the component object which is used in conjunction with the pointer to the Device portion of the protective device Parts object. It is associated with each protective device component *i* , *i* = 1, 2, 3 ... .
Sptr_Curve	Starting pointer to an object of type protective curve that is also the first object in the linked list of objects of type protective curve.
Sptr_Device	Starting pointer to an object of type protective device that is also the first object in the linked list of objects of type protective device.
pCmp	Pointer to a Component object.
pFa	A data structure member of the Component object that is a pointer to a Fault Analysis Object, i.e. ***FA1, FA2, ... , FA14.***
FAi	Fault Analysis Objects that contains results from fault analysis and are attached to every component that is processed, *i* = 1, 2, ... 14.
pPo	A data structure member of the Component object that is a pointer to a Placement Object, i.e. ***PO1, PO2, ..., PO8***.
POi	Placement Objects that contain data results from placement function and are attached to every component that is a protective device location , *i* = 1, 2, ... 8.
pRa	A data structure member of the Component object that is a pointer to a Reliability Object that is defined as ***RA***.
RA	Reliability Object that contain data results from reliability analysis and are attached to Component Objects.

6.6.2 Accessing Engineering Analysis Function Data

As indicated in Section 6.3, the application of placement and selection rules depends upon interfaces to engineering analysis functions. Similar to the linking of Parts data to components, engineering analysis objects are linked to component objects for which they apply. Figure 6.10 illustrates the links between engineering analysis objects and the component object to which they apply. Not every component object has a link to every type of analysis object. For instance, capacitors objects are linked to the power flow analysis, but they are not linked to the fault analysis. The sharing of data among the different engineering functions is implemented through the links to the common component object.

Every component object of type line section is linked to a fault analysis object. Table 6.5 illustrates example information stored in a fault analysis object. All configurations are considered in deriving the information shown in Table 6.5. If ***pCmp*** points to a component object of type line section. Then, after fault analysis has run, the absolute maximum phase fault current associated with a component object ***pCmp*** may be obtained by

pCmp->pFa->FA13 . [6.5]

In an interconnected system of radial distribution circuits, the position of the switches within the system determines its configuration at any given time. The Configuration object shown in Figure 6.10 is attached to component objects of type switch. The Configuration object stores the switch position for each configuration to be considered by the analysis. If the switching data presented in Table 4.3 represents all the switches in an interconnected system of radial circuits, five Configuration objects exist for the system, i.e. SW 117, SW 234, SW 354, SW 789, and SW 857; and each Configuration object will contain the switch position for five configurations that represent five distinct time points as defined by CONF_ID of *-1*, *1*, *2*, *3*, and *4*.

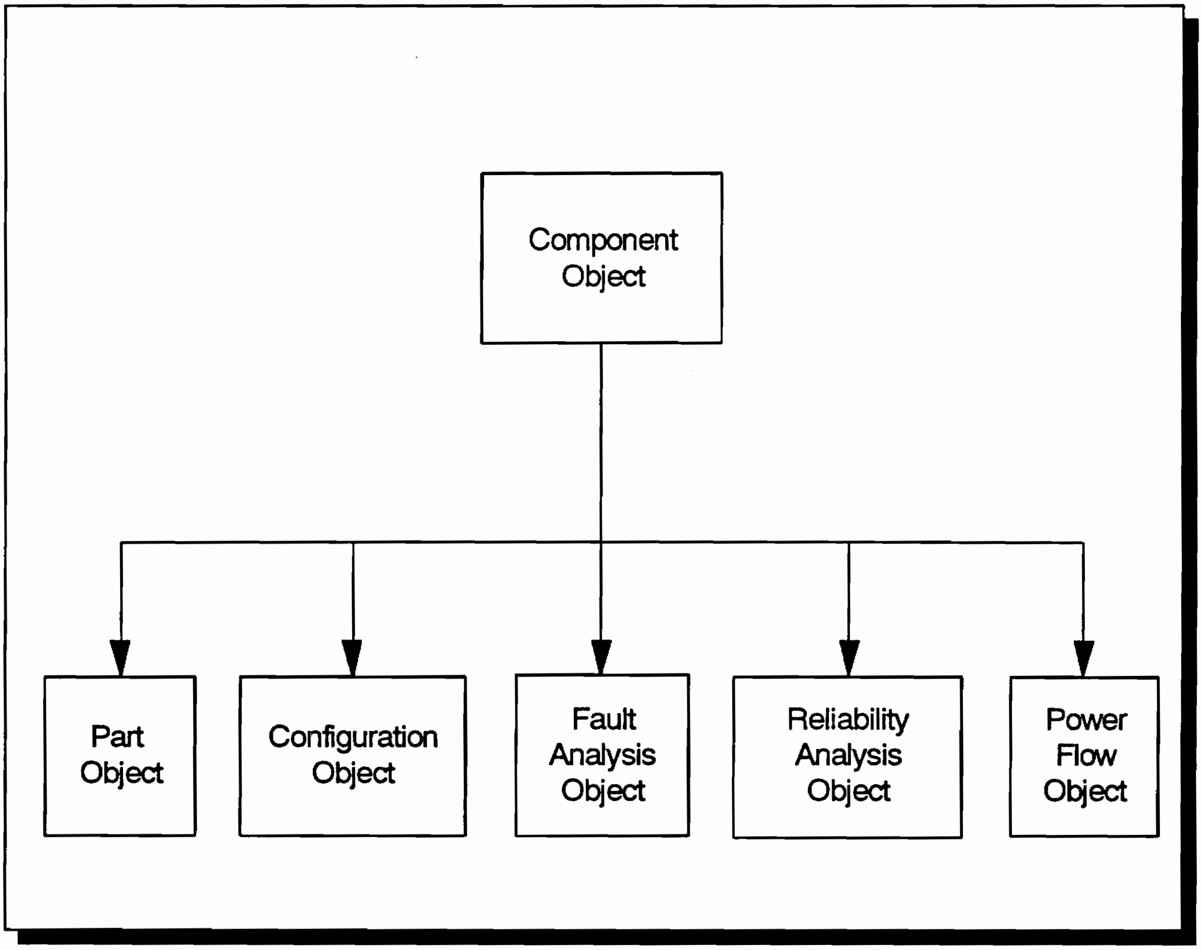

Figure 6.10. Sharing of Data Among Engineering Analysis Objects

Table 6.5. Variables in Fault Analysis Objects

Variable	Description of Variable
FA1	Maximum Forward direction Phase fault current calculated by Fault Analysis through a circuit component.
FA2	Maximum Forward direction Ground fault current calculated by Fault Analysis through a circuit component.
FA3	Maximum Forward direction fault current calculated by Fault Analysis through a circuit component, based on values of ***FA1*** and ***FA2***.
FA4	Minimum Forward direction Phase fault current calculated by Fault Analysis through a circuit component.
FA5	Minimum Forward direction Ground fault current calculated by Fault Analysis through a circuit component.
FA6	Minimum Forward direction fault current calculated by Fault Analysis through a circuit component, based on values of ***FA4*** and ***FA5***.
FA7	Maximum Reverse direction Phase fault current calculated by Fault Analysis through a circuit component.
FA8	Maximum Reverse direction Ground fault current calculated by Fault Analysis through a circuit component.
FA9	Maximum Reverse direction fault current calculated by Fault Analysis through a circuit component, based on values of ***FA7*** and ***FA8***.
FA10	Minimum Reverse direction Phase fault current calculated by Fault Analysis through a circuit component.
FA11	Minimum Reverse direction Ground fault current calculated by Fault Analysis through a circuit component.
FA12	Minimum Reverse direction fault current calculated by Fault Analysis through a circuit component, based on values of ***FA10*** and ***FA11***.
FA13	Absolute Maximum fault current calculated by Fault Analysis through a circuit component. The value is determined from the Maximum value of ***FA3*** and ***FA9***.
FA14	Absolute Minimum fault current calculated by Fault Analysis through a circuit component. The value is determined from the Minimum value of ***FA6*** and ***FA12***.

6.7. Inference Engine

A block diagram of the inference engine rule processors and interfaces is shown in Figure 6.11. The Coordination, Selection, and Placement rule processors are run as separate functions. The Selection Rule Processor depends upon having the Coordination data produced by the Coordination Rule Processor. However, the Coordination Rule Processor does not need to be run each time the Selection Rule Processor is run.

In selecting locations for the placement of devices, the designer may perform any combination of the following: let the Placement Rule Processor select locations; select locations himself via the GUI; or let the Placement Rule Processor select locations and then use the GUI to modify locations selected by the Placement Rule Processor. The Selection Rule Processor needs locations specified at which devices are to be selected. However, the Placement Rule Processor does not need to be run to select those locations.

Rule processors in the inference engine are implemented with two modes which are a procedural mode and a declarative, or query, mode. The terminology "procedural mode" implies that a function is implemented with a series of steps. The procedural mode is implemented in the C language. With the query mode functions are implemented with a single high level computer language statement. The query mode is implemented using the Structured Query Language (SQL) [39].

6.7.1 Coordination Rule Processor

Coordination data is created by the Coordination Rule Processor of the inference engine from protective device data stored in the Device and Curve tables, shown in Tables 5.1 and 5.2, respectively. The Coordination Rule Processor applies the rules from Table 6.1 to protective device data stored in the Device and Curve tables and produces a Coordination Table. The Coordination Table is stored in the relational database of DANE. The

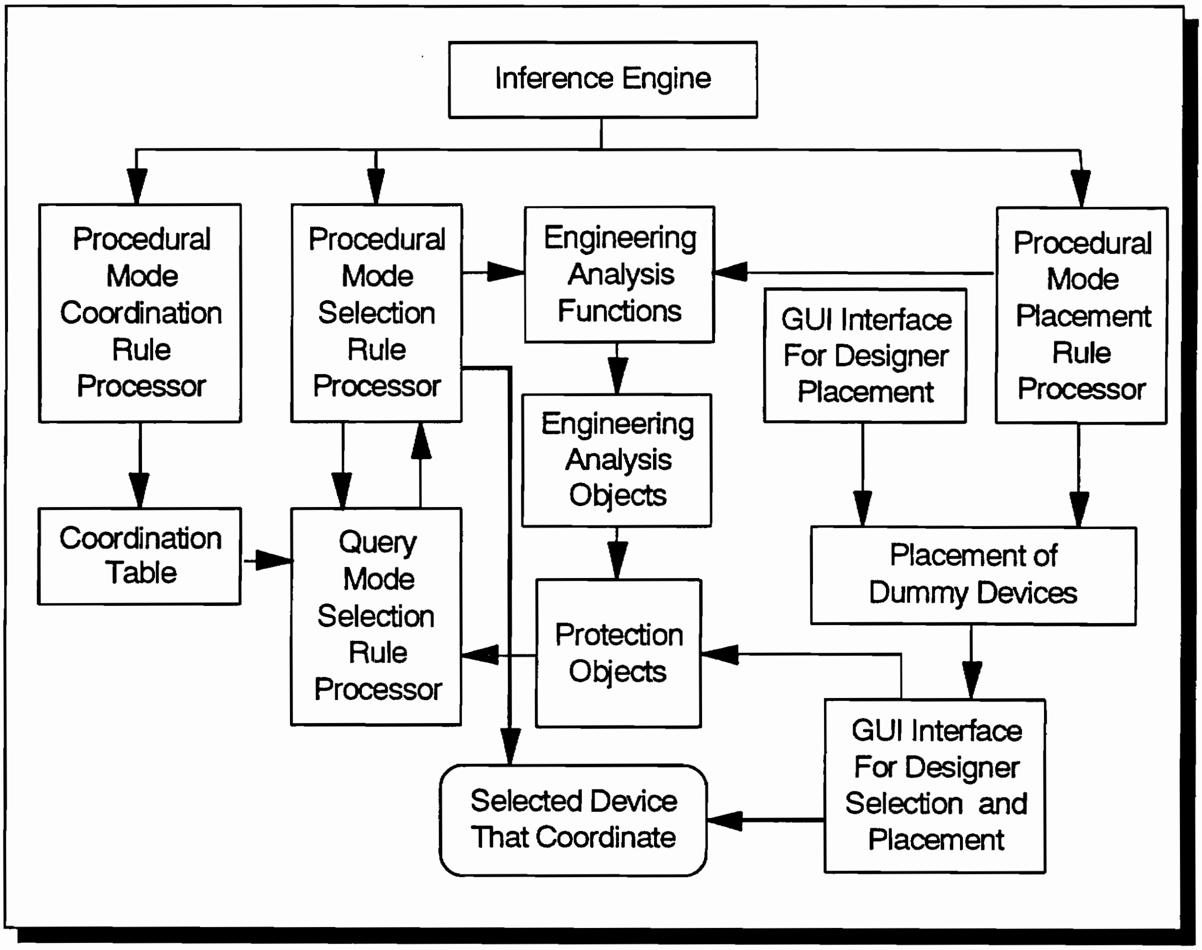

Figure 6.11. Inference Engine Rule Processors and Interfaces

information contained in the Coordination Table is given by Table 6.6. As illustrated later in this chapter, the data from the Coordination Table is utilized by the query mode of the Selection Rule Processor. The Coordination Rule Processor is written entirely in the C language.

During its analysis, the Coordination Rule Processor examines two TCC curves. As indicated by the column headings in Table 6.1, one curve is referred to as the Primary curve and the other is referred as the Backup curve. The nomenclature used in conjunction with the two curves essentially represents the physical circuit location of two protective devices -- the Primary and Backup protective devices. Thus, some portion of the Primary curve should always lie below the Backup curve if the devices are to coordinate with each other. The only exception to this rule occurs for *C2* , which is addressed in the next section of this report.

The TCC curves used in this research were modeled from a series of digitized x,y points where x represented amperes and y represented time in seconds. A maximum of 40 points was used in the modeling of each TCC curve. Thus, a TCC curve is represented by a series of piecewise linear lines. However, when the various TCC curves were digitized, the points were chosen at random. Thus, there was no pattern of alignment between the different TCC curves. As a result the Coordination Rule Processor aligns the two curves that are being processed. The alignment is along the x-axis such that the value for amperes match on both *TCC* curves. The alignment of the TCC curves alignment must be performed at every x,y point of a TCC curve that is analyzed by the Coordination Rule Processor.

The Coordination Rule Processor uses the Primary curve as the basis for checking coordination between device curves. For a given value of amperes on the Primary curve, the Backup curve is interpolated along such that its new value for amperes matches that specified by the Primary curve. For the new value of interpolated amperes the Backup curve will also have a new corresponding operational time.

Table 6.6. Coordination Table

Variable	Definition of Column Contents
Backup_Device	Key into Device Table that identifies the Backup device. Using the Backup's Device object, the value is obtained from ***Device***->*Device.*
Backup_Curve	Key into Curve Table that identifies all curves associated with the Backup device. Using the Backup's Curve object, the value is determined from ***Curve***->*Curve.*
Backup_Type	Identifies the type of Backup device. Using Backup's Device object, the value is obtained from ***Device***->*Type.*
Backup_Amps_Rating	The continuous amperes rating for the backup device. Using the Backup's Device object, the value is determined from ***Device***->*Amps_Rating.*
Backup_Volt_Rating	The voltage rating for the backup device. Using the Backup's Device object, the value is obtained by ***Device***->*Volt_Rating.*
Primary_Device	Key into Device Table that identifies primary device. Using the Primary's Device object, the value is obtained by ***Device***->*Device.*
Primary_Curve	Key into Curve Table that identifies all curves associated with the primary device. Using the Primary's Curve object, the value is determined from ***Curve***->*Curve.*
Primary_Type	Identifies for the type of primary device type. Using the Primary's Device object, the value is obtained from ***Device***->*Type.*
Primary_Amps_Rating	The continuous amperes rating for the primary device. Using the Primary's Device object, the value is determined from ***Device***->*Amps_Rating.*
Primary_Volt_Rating	The voltage rating for the primary device. Using the Primary's Device object, the value is obtained from ***Device***->*Volt_Rating.*
Min_Coord_Amps	The minimum amperes for which the Backup and Primary curves coordinate, determined by Coordination Rule Processor.
Max_Coord_Amps	The maximum amperes for which the Backup and Primary curves coordinate, determined by Coordination Rule Processor.
Max_Time_Diff	The maximum time separation between the Backup and Primary curves, determined by Coordination Rule Processor.

If *CT_Primary*[*iAmps*] and *CT_Backup*[*iAmps*] represent the operational time of the Primary and Backup devices, respectively, for a specific value of amperes, the difference between the operational times of the Primary and Backup curves, *Delta_Time*, is given by

$$\mathit{Delta\_Time} = \mathit{CT\_Backup}[\mathit{iAmps}] - \mathit{CT\_Primary}[\mathit{iAmps}] \ . \qquad [6.6]$$

A positive value for *Delta_Time* implies that the device pair coordinate at the given value of amperes. The Coordination Rule Processor repeats the interpolation procedure on the Backup curve using the next value of amperes specified by the Primary curve. The Coordination Rule Processor stops checking the pair of device curves whenever the value for *Delta_Time* becomes negative.

The Coordination Rule Processor performs an initial check to alleviate part of its processing load. By initially checking the endpoints of the Primary and Backup curves, numerous Primary and Backup curve combinations can rapidly be eliminated from consideration. Additionally, if a pair of curves require further analysis by the Coordination Rule Processor, the optimal starting point for the analysis is defined at this juncture.

The Coordination Rule Processor initially examines the endpoints of the Primary and the Backup curves. Device coordination is not checked if the Primary curve's maximum amperes are less than the Backup curve's minimum amperes, or the Primary curve's minimum amperes are greater than the Backup curve's maximum amperes. For these two conditions no overlap exists between the Primary and Backup curves and no coordination exists, and the new Backup device is checked against the Primary. Assuming that some overlap exists between the Primary and Backup curves, the Coordination Rule Processor calculates their time difference, i.e. *Delta_Time*, at the two endpoints of the Primary curve and the Backup curve.

Four possible cases exist at this stage of the comparison as illustrated in Figure 6.12. In CASE 1, the Backup and Primary curves coordinate at the minimum amperes value of the Primary curve. The Coordination Rule Processor begins its analysis at the optimal starting location, the minimum amperes value on the Primary curve. The analysis for the curve pair concludes when *Delta_Time* becomes negative. For CASE 2, the Backup and Primary curves coordinate at the maximum amperes value of the Primary curve and the analysis starts at the maximum amperes value on the Primary curve. The analysis continues along the Primary curve until *Delta_Time* becomes negative. Notice that the value of amperes is constantly decreasing in CASE 2 as opposed to constantly increasing in CASE 1. The Coordination Rule Processor is able to process the device curves in either direction.

For CASE 3 , the Backup and Primary curves coordinate at both the endpoints. However, the Coordination Rule Processor starts at the minimum value of amperes and checks device coordination. It was observed during this research that even though both endpoints of the Primary and Backup curves coordinated there were some rare instances in which the Primary and Backup curves failed to coordinate at the center portion of their curves. Recloser device curves were involved in all of these occurrences . For CASE 4, the Primary and Backup curve fail to coordinate at either endpoint, and the Coordination Rule Processor get a new Backup device from the table.

Based upon the rules being processed, for each device in the Device Table the corresponding curve from the Curve Table is compared with all other device curves. If Rule ***C13*** is turned on and Rule ***Ci*** is also turned on, then a logical *AND* condition is used to determine if coordination is satisfied, as given by

$$L = C13 \ AND \ Ci \ . \qquad [6.7]$$

If L evaluates to *TRUE*, then a new row is added to the Coordination Table.

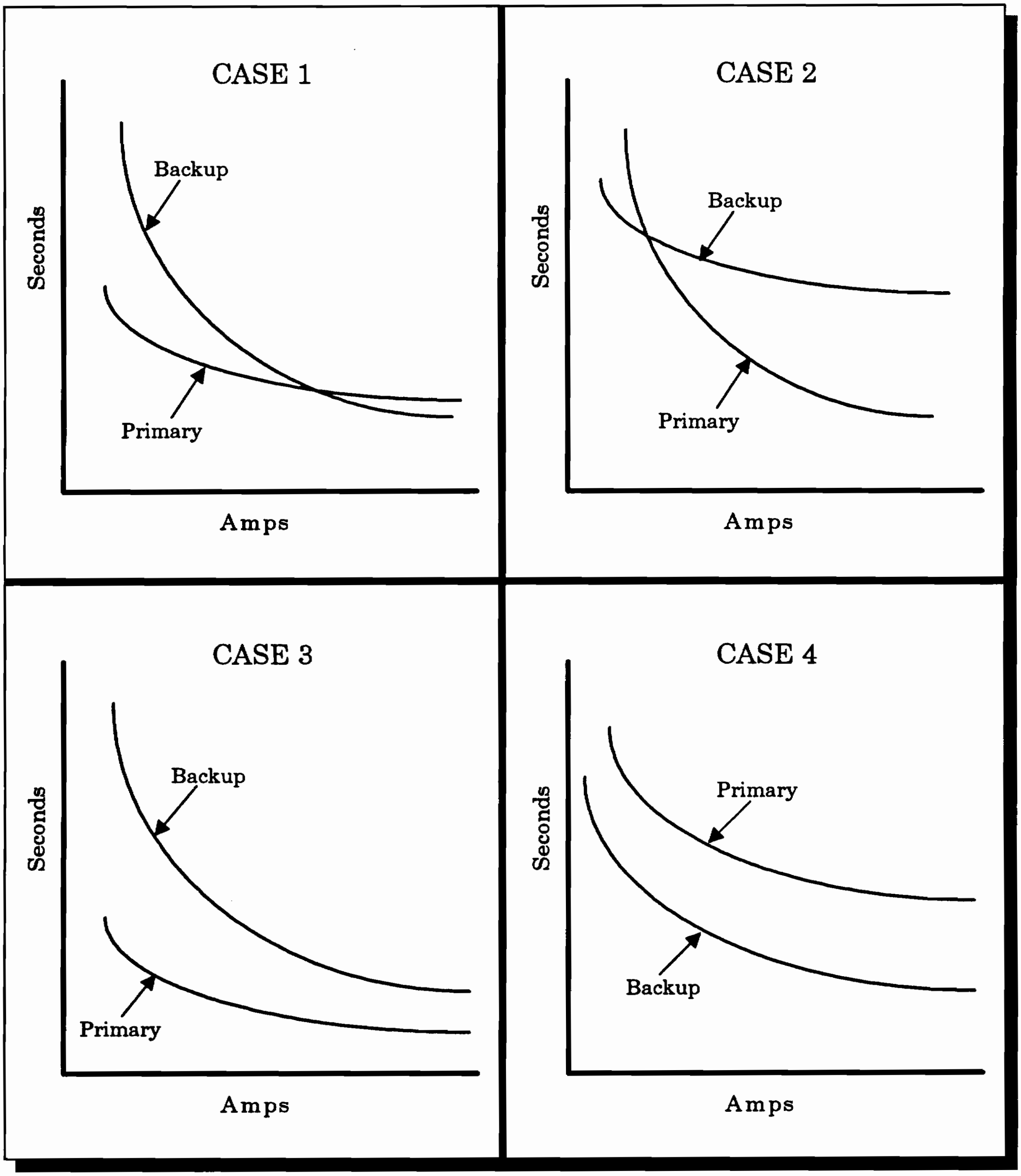

Figure 6.12. Four Possible Cases for the Coordination of TCC Curves

The only data in the Coordination Table that is developed by the calculations of the Coordination Rule Processor are the values for *Min_Coord_Amps*, *Max_Coord_Amps*, and *Max_Time_Diff*. The remaining data for the Coordination Table is determined by accessing the Device and Curve objects. For instance, to obtain the value for *Backup_Amps_Rating* the Device object is access as shown by

$$(\mathbf{Sptr\_Device} + (\mathbf{pCmp}\text{->}Device\_Offset_i))\text{->}Amps\_Rating \qquad [6.8]$$

where $Device\_Offset_i$ is the row number of the Backup device in the Device Table. The specific data objects, that are used in the development of the Coordination Table data, are shown in Table 6.6,

The Coordination Table can become very large due to numerical combinations of the protective devices stored in the two tables. To illustrate this point, consider the following: Assume that there are three classes of relays stored in the Device Table, that each class has three styles, and that there are eight taps and twelve Time Dial curves for each style. Hence, there are seventy-two rows in the Device Table and thirty-six rows in the Curve Table associated with relays. However, there are a total of 864 different curves that may be selected for relays. Also assume that there are six reclosers, and that each recloser has six trip coils and three curves. Hence, there are 108 different curves that may be selected for reclosers. Finally, assume there are 200 fuses stored in the Device Table, and thus 200 curves that may be selected for fuses. If all curves would coordinate, these numbers would lead to 1.37E6 rows for the Coordination Table.

Any of the rules processed by the inference engine may be turned on or off. Turning off coordination rules will affect the data contained in the Coordination Table, and hence the data available to the selection process. For instance, if the designer did not wish to have coordination between relays and fuses considered, then rules ***C4*** and ***C9*** would be turned off.

The Coordination Table only needs to be updated when data is modified in the Device or Curve tables, or when the designer changes any of the coordination parameters or rules to apply, described in Table 6.1. The Coordination Rule Processor is part of the integrated expert system, but it can also be run as an independent workstation application. Thus, a user can used it independently to check the coordination among various protective devices .

6.7.2 Fuse and Recloser Coordination

The coordination between a fuse and recloser is a special condition when a recloser is serving as the backup device. The Fast Trip curve of the recloser should react to clear all transient fault conditions within the fuse's primary protection zone. This prevents needless damage to the fuse. The recloser must perform a fast trip operation before any operation occurs on the Melting curve of the fuse. However, if the fault is permanent in nature, the fuse must still react as the primary device and clear the fault within its protection zone.

The TCC curves for a fuse and recloser are illustrated in Figure 6.13. The example presented in Figure 6.13 depicts both the Clearing and Melting curves for the fuse and the Fast Trip and Delayed Trip curves for the recloser. The TCC curves shown in Figure 6.13 should coordinate over the entire range of expected fault currents for the fuse. The range of expected fault currents is labeled on the x-axis in the diagram. Coordination rules ***C2*** and ***C3*** apply to the time separation between the different pairs of curves shown in Figure 6.13.

To prevent fuse damage and permanent outages due to momentary faults, a recloser typically performs multiple operations on its Fast Trip curve before it "lockouts". For this situation, the recloser's Fast Trip curve should lie below the fuse's Melting curve over the range of expected fault currents. Thus, if a fuse is the primary device, the recloser will initially operate on its Fast trip curve and attempt to clear the fault. ***C2*** controls the separation between the fuse and recloser curves by scaling the fuse Melting curve.

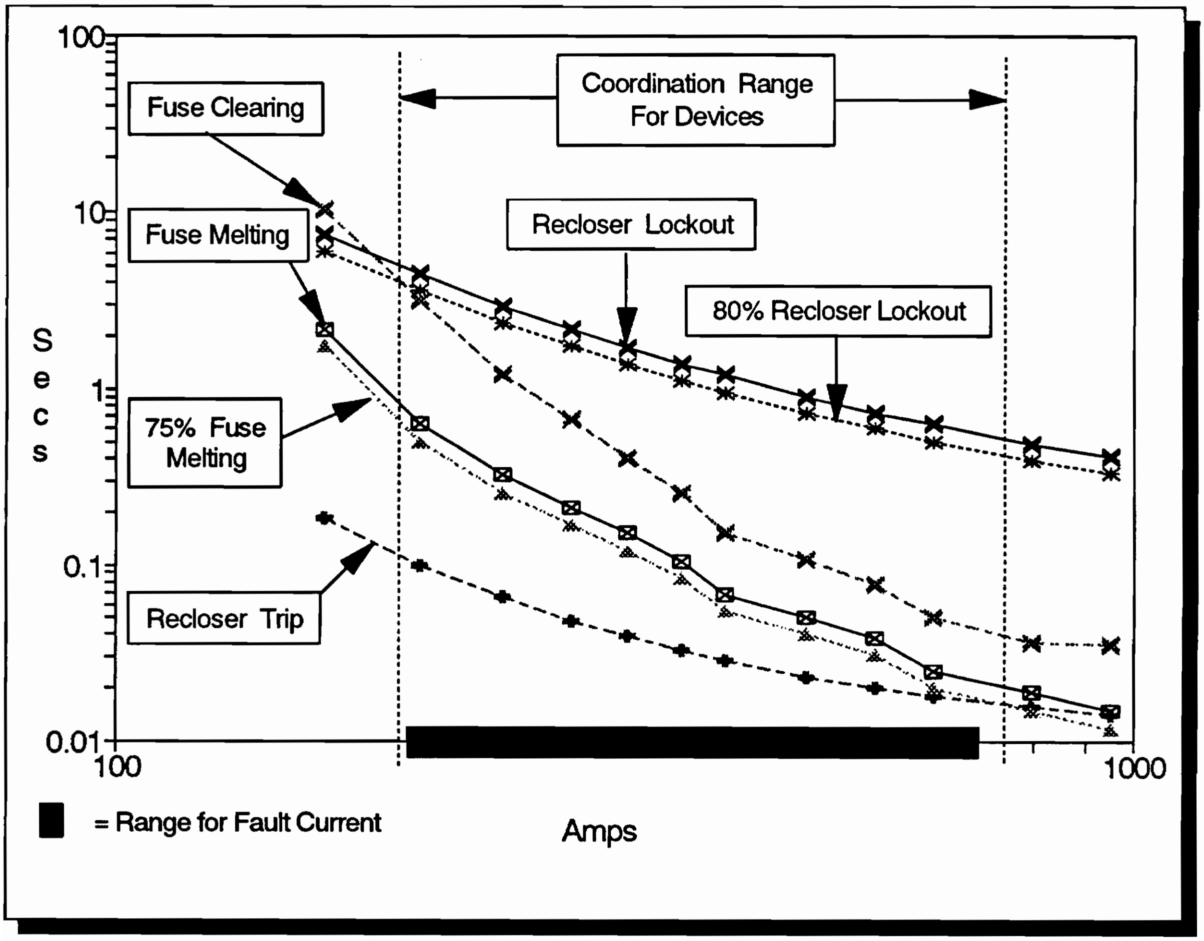

Figure 6.13. Primary Fuse and Backup Recloser Coordination

The effect of setting the coordination parameters for **C2** at 75% and **C3** at 80% is shown graphically in Figure 6.13. The time points of the fuse's Melting curve are scaled by 75% due to **C2**. The recloser's Fast Trip curve intersects with the fuse's Melting curve at approximately 750 amperes. This point of intersection sets the value of *Max_Coord_Amps*. The time points of the recloser's Delay Trip curve are scaled by 80% due to **C3**. The recloser's Delay Trip curve intersects with the fuse's Clearing curve at approximately 150 amperes. This determines the value of *Min_Coord_Amps*. As shown in Figure 6.13, the coordination range between the fuse and recloser is capable of providing the required protection for the expected range of fault current amperes.

6.7.3 Placement Rule Processor

Every component in the system of interconnected circuits is evaluated by the Placement Rule Processor for possible protective device locations. Locations for the placement of devices are determined based upon the topology of the interconnected circuits. The topology of the circuits is processed by working from the ending branches of each circuit toward the substation. Circuit traces, which process the linked list of components that comprise the circuit, are used in this process of analysis [47]. The Placement Rule Processor inserts a "dummy device" at a circuit location whenever any of the activated placement rules, except *P3*, are satisfied during the analysis.

To determine locations for protective devices, the Placement Rule Processor uses a logical *OR* condition in evaluating all activated placement rules. For example, if placement rules ***P1, P2, P3, P5, P6,*** and ***P8,*** defined in Table 6.2, are activated, then the logic evaluated is given as

$$\boldsymbol{L} = \boldsymbol{P1} \ \mathit{OR} \ \boldsymbol{P2} \ \mathit{OR} \ \boldsymbol{P3} \ \mathit{OR} \ \boldsymbol{P5} \ \mathit{OR} \ \boldsymbol{P6} \ \mathit{OR} \ \boldsymbol{P8} \ . \qquad [6.9]$$

If ***L*** is evaluated *TRUE*, a dummy device is graphically inserted at the circuit location.

The evaluation of the placement rules by the Placement Rule Processor involves every component in the circuit, but many of the activated placement rules only apply to a specific type of component. For instance, ***P1*** is only evaluated if the component is the start of the circuit. Similarly, ***P2*** is only checked when the component is some type of transformer. ***P4*** is only valid during the analysis process if the component is the start of a lateral, and ***P8*** is only applicable to tie-line sections of the circuit.

Only ***P5***, ***P6***, and ***P7*** are applicable to all circuit components. As indicated in Table 6.2, ***P5***, ***P6***, and ***P7*** use external data produced by other analysis functions during the evaluation process. ***P5*** uses the Fault Analysis objects ***FA5*** and ***FA6*** to determine if a protective device is required at given component location. If *P5_Paramter_Value* defines the parameter value associated with ***P5***, then the relational equation to determine device placement is given by

$$\boldsymbol{L} = \{ \mathit{P5\_Paramter\_Value} < \boldsymbol{pCmp\text{->}pFa\text{->}FA5} \ / \ \boldsymbol{pCmp\text{->}pFa\text{->}FA6} \} \qquad [6.10]$$

and if ***L*** evaluates *TRUE*, a dummy device is placed at the circuit location.

P6 uses available customer information data in evaluating device placement. The customer information data contains the number and type of customers attached to a specific line section. As shown in Figure 6.10, a Reliability Analysis object, i.e. ***RA***, is attached to circuit Component objects. ***RA*** objects are used by ***P7*** during the placement analysis. If *P7_Paramter_Value* defines the parameter value associated with ***P7***, then the relational equation used to evaluate device placement is given by

$$\boldsymbol{L} = \{ \mathit{P7\_Paramter\_Value} < \boldsymbol{pCmp\text{->}pRa\text{->}}\mathit{Failure\_Rate} \} \qquad [6.11]$$

where ***pRA*** is defined in Table 6.4 and *Failure_Rate* is a data structure member of the ***RA*** object. A device is placed at the circuit location if ***L*** evaluates *TRUE*.

Although ***P3*** is shown in Table 6.2 as a placement rule, its function is to remove unnecessary protective devices from the circuit.

After the Placement Rule Processor completes the analysis of the circuits, the placement of the dummy devices is graphically displayed to the designer. The designer may also use the GUI to insert and delete dummy devices. After the locations for the dummy devices have been finalized, the Placement Rule Processor creates the data for the Protection Objects shown in Table 6.7.

For each protective device location, a Protection Object is created and attached to the protective device. Data contained in Fault Analysis and Power Flow Objects are used in the creation of the Protection Objects. ***PO1*** is formed by considering the ***FA13*** of all components within a primary protection zone. For instance, consider a primary zone comprised of *n* components and let *j* represents a component in the protection zone such that *j*= 1, 2, ... *n*. The value of ***PO1*** can be determined using the following relationship

$$\boldsymbol{PO1} = \mathrm{MAX}\ \{\ \boldsymbol{pCmp_j\text{->}pFa\text{->}FA13}\ ,\ j=1,\ 2,\ \ldots\ n\ \}\ . \qquad [6.12]$$

Within a given protection zone, a set of calculated peak load currents and cold load inrush currents will exist for each component. The Power Flow object, defined as ***PF***, contains the peak load current, *Peak_Load_Amps* and the cold load inrush current, *Cold_Load_InRush*. For a protection zone consisting of *n* components, ***PO2*** is derived from the Power Flow objects associated with the group of *n* components. If *j* represents a component in the protection zone such that *j*= 1, 2, ... *n*, the value of ***PO2*** is determined by

$$\begin{aligned}\boldsymbol{PO2} = \mathrm{MAX}\ \{&\boldsymbol{pCmp_j\text{->}pPf\text{->}PF\text{->}}\mathit{Peak\_Load\_Amps}\ ,\\ &\boldsymbol{pCmp_j\text{->}pPf\text{->}PF\text{->}}\mathit{Cold\_Load\_InRush}\ \ \}\end{aligned} \qquad [6.13]$$

where ***pPf*** is a component pointer to the Power Flow object and *j* = *1, 2, ... n*.

The method in which ***PO3*** is determined parallels the previous discussion concerning ***PO2***. The only difference being that ***PO3*** is determined from ***FA4***and ***FA7***, i.e. the minimum Forward and Reverse Phase fault currents, of all the components within a primary protection zone. Similar to Equation 6.10, the value of ***PO3*** is given by

$$\boldsymbol{PO3} = \mathrm{MIN}\ \{ \boldsymbol{pCmp_j\text{->}pFA\text{->}FA4}\ , \quad \boldsymbol{pCmp_j\text{->}pFA\text{->}FA7} \ \} \qquad [6.14]$$

where $j = 1, 2, \ldots n$.

The intent behind the formulation of the data stored in ***PO4*** seeks to provide additional protection. In the event that a primary protective device fails to operate for a fault, it is necessary that its backup protective device operate to clear the fault. Thus, the information stored in ***PO4*** is based on two protection zones, the primary and backup protection zones. ***PO4*** stores the minimum value for ***FA14*** within a protective device's primary and backup zones. If a device's primary and backup zones consist of *m* components, the expression for determining ***PO4*** is given by

$$\boldsymbol{PO4} = \mathrm{MIN}\ \{ \boldsymbol{pCmp_j\text{->}pFa\text{->}FA14},\ j=1, 2, \ldots m \}\ . \qquad [6.15]$$

The purpose for ***PO5*** is related to the same principle as ***PO4*** -- additional protection. ***PO5*** contains the minimum equipment amperes rating of all components within a protective device's primary and backup zones. ***PO5*** is determined from Power Flow objects using the equipment amperes rating, defined as *Equip_Amps_Rating*. For *m* components that exist within a device's primary and backup zones, the value of ***PO5*** is determined using

$$\boldsymbol{PO5} = \mathrm{MIN}\ \{ \boldsymbol{pCmp_j\text{->}pPf\text{->}PF\text{->}}\mathit{Equip\_Amps\_Rating} \} \qquad [6.16]$$

where ***pPf*** is a component pointer to the Power Flow object and $j = 1, 2, \ldots m$.

At each protective device location, ***PO6*** contains the minimum from the set of values for downstream ***PO4*** and ***PO5***. The reference to downstream implies that all protection zones are included until the ending zone is reached during the analysis. Thus, the last zone always includes an ending branch component. If all of the downstream protection zones consist of m components and j is a component within the protection zones, ***PO6*** is determined using Equations 6.13 and 6.14 and is given by the following relationship

$$\boldsymbol{PO6} = \text{MIN} \left\{ \boldsymbol{pCmp_j\text{->}pFa\text{->}FA14} \ , \quad \boldsymbol{pCmp_j\text{->}pPf\text{->}PF\text{->}}Equip\_Amps\_Rating \right\} \qquad [6.17]$$

where ***pPf*** is a component pointer to the Power Flow object and $j = 1, 2, \ldots m$.

A relationship exists between ***PO2***, ***PO3***, ***PO4***, and ***PO6*** that pertains to the topic of ground tripping devices. Consider the following example based on the data in the Protection Objects. If a fuse device is chosen based solely upon the information stored in ***PO4***, the fuse may not operate properly. If the value of ***PO2*** exceeds ***PO4***, the fuse will incorrectly sense load current as a fault and improperly operate. As indicated earlier in the report, the condition -- of improper protective device operations due to load currents -- is the predominant cause of false operations and mis-coordination in existing protection system [1]. Whenever the value of ***PO2*** exceeds ***PO4*** a fuse device is not capable of providing total fault current protection. For this situation what is referred to as ground trip reclosers are utilized in conjunction with fuses to provide fault protection. If a recloser ground trip is used , the data in ***PO3*** is crucial to the fuse selection. The phase device must still interrupt the minimum phase fault current. The data in ***PO6*** dictates the setting for minimum pickup on the ground trip of the recloser. Thus, the data from ***PO2, PO3***, ***PO4***, and ***PO6*** must be examined and special conditions exist whenever ***PO2*** exceeds ***PO4***. As indicated in Table 6.7, the data contained in the Protection Objects is utilized by the Selection Rule Processor.

Table 6.7. Description of Protection Objects

Variable	Description of Information	Rules
PO1	Stores the Absolute Maximum fault current in a protective device's primary zone. The informational data is based on each component's Fault Analysis object value for ***FA13***.	***S13***
PO2	Defines the Maximum between the peak load and the cold load inrush current in a protective device's primary zone. The value stored is based on each component's Power Flow object values of *Peak_Load_Amps* and *Cold_Load_InRush*.	***S9, S12, S13***
PO3	Contains the Minimum phase fault current in a protective device's primary zone. The informational data is based on each component's Fault Analysis object values for ***FA4*** and ***FA7***.	***S8***
PO4	Defines the Minimum between the Primary and Backup zone Absolute Minimum fault currents. The informational data is based on each component's Fault Analysis object value for ***FA14***.	***S4***
PO5	Defines the Minimum between the Primary and Backup zone equipment current ratings. The value stored is determined based on each component's Power Flow object value for *Equip_Amps_Ratings*.	***S5***
PO6	Contains the downstream minimum value of Absolute Minimum fault current or equipment current rating that must be protected by a recloser. The informational data is determined from the set of each component's Fault Analysis object value for ***FA14*** and each component's Power Flow object value for *Equip_Amps_Ratings*.	***S8***

6.7.4 Selection Rule Processor

The Selection Rule Processor has two modes of operation, a query mode and a procedural mode. The procedural mode is implemented using the C programming language, and the query mode is implemented with ESQL statements. The logic flow diagram for the Selection Rule Processor is presented in Figure 6.14. The goal of the Selection Rule Processor is to select protective devices that coordinate at all placement locations. The dummy protective devices inserted by either the Placement Rule Processor or the designer act as place holders. For each dummy device, the Selection Rule Processor attempts to select an actual device to replace the dummy device.

The concept of protective device level is used by the Selection Rule Processor, where level is defined as follows:

> *The level of a given protective device is the maximum number of protective devices between the given protective device and an ending branch of the circuit.*

As shown in Figure 6.14, the first task that the Selection Rule Processor must perform is the determination of each device's level. When performing a reverse trace from an ending branch, the first device encountered, whether it be an actual or dummy device, is marked as level zero. As the reverse trace continues, the next device encountered is marked as a level one device, and so forth. In tracing from one ending branch a device may be a level two device, but in tracing from another ending branch the same device may be a level three device. In such a case the device is labeled as a level three device.

Protective devices are selected for one circuit at a time. For each circuit that is being processed the Selection Rule Processor initializes program variables. Additionally, as shown in Figure 6.14, the value for PO_Flag is set to YES to indicate that the Selection Rule Processor use fault current data from the Protection Objects. If PO_Flag is set to NO, the

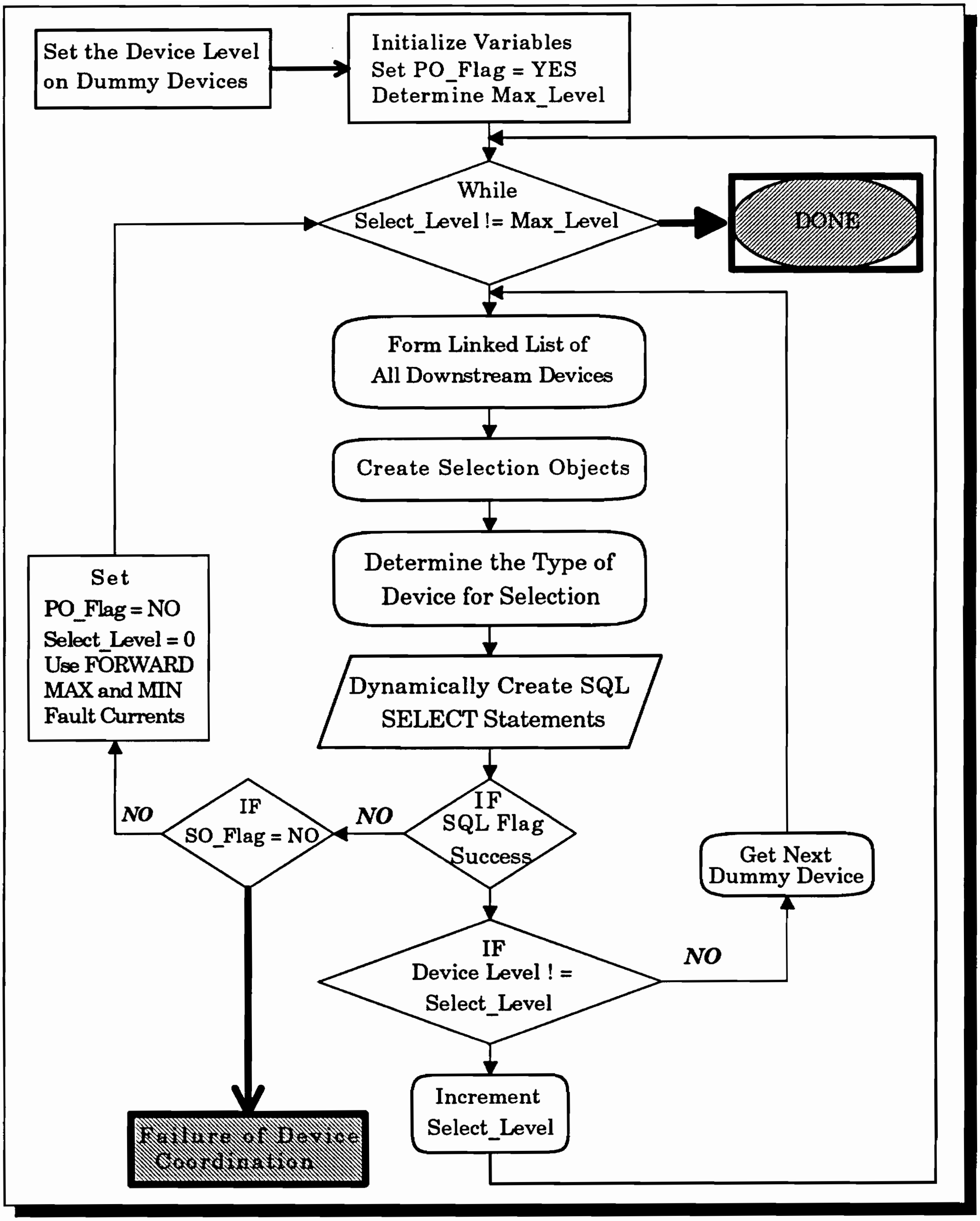

Figure 6.14. Selection Rule Processor Flow Diagram

fault currents are obtained from Fault Analysis objects. The purpose in PO_Flag will become evident in the preceding discussion of this section. The value of Max_Level is initialized to the maximum protective device level in the circuit being processed.

The Selection Rule Processor works from the ending branches of each circuit toward the substation. The selection rule processor begins selecting devices at level zero. Thus, the variable Select_Level starts at zero. As shown in Figure 6.14, the selection process continues for a given circuit until Select_Level reaches Max_Level. Each time an actual device is selected, it must selected such that it coordinates with all downstream devices. In order to accomplish this coordination, the Selection Rule Processor forms a linked list of all downstream devices. If the device being selected has Select_Level equal zero, the linked list will contain devices, only if the selected device is a tie_line component, and actual protective devices exist in adjacent tie_line connecting circuits. Tie_line protective devices at level zero, that may be switched to an adjacent circuit, must be checked for coordination with the corresponding level zero devices in the adjacent circuit.

A Selection Object is created from this linked list of devices. The Selection Object is developed at the selected device location based on information from the linked list of downstream devices, activated selection rules, previously selected devices, and the value of PO_Flag. The Selection Object only contains information that is valid and must be processed at the given device location. For example, if the device being selected is a recloser and only fuses have been selected at downstream locations, all of the data in the linked list would apply to the device's selection. Recall that a recloser must provided backup protection to all downstream fuse protected zones as discussed previously in Section 6.7.2 and illustrated by Figure 6.13. However, if the device being selected is a fuse, then the only downstream devices in the linked link that would be valid and contained in the Selection object would be those that are one protection zone below the fuse being selected, since a fuse must only serve as backup for one protection zone beyond its primary protection zone.

Information about previously selected devices and designer implemented Selection Rules also determine valid data for the device's Selection Object. If number of downstream selected fuses equals the designer's specified value contained in the parameter of ***S11***, the Selection Object must contain information for a backup recloser device selection. If a recloser exist downstream, the device's Selection Object does not need information to provide for backup recloser selection. The Selection Object also contains circuit criteria data such as the operating voltage at the selected device's location, the number of phases, and the type of line construction, either underground or overhead.

Selection Object information is used to dynamically create SQL Select statements. The query mode of the Selection Rule Processor uses SQL Select statements which query the Coordination Table. When performing device selection, the selected device must serve as the backup device for all devices specified by the device's Selection Object. As such, the selected device may serve as the backup protective device for one or several downstream protective devices.

Rules ***S1***, ***S3***, ***S7***, ***S8*** and ***S10*** are implemented by the procedural mode, and the remaining rules are implemented with the query mode. The procedural mode determines which query mode select statement needs to be utilized by the Selection Rule Processor. For example, if rule ***S10*** is activated and its selection parameter is set to select relays at the start of the circuit, the procedural mode activates a select statement for this rule. Thus, when the Selection Rule Processor analysis reaches the start of the circuit the select statement used will only select relays.

When evaluating possible devices to select from the Coordination Table, all of the activated selection rules must be satisfied. Thus, the Selection Rule Processor uses a logical

AND condition for the evaluation. The *AND* condition is implemented in the conditional portion of the SQL Select statement, as indicated in Figure 6.15.

To distinguish between different portions of the Select statement in Figure 6.15 the following format for the font typeface is used:

bold words indicate SQL Select statement qualifiers; <u>underlined</u> words indicate from which table to select data; *italics* words indicate specific columns in the selected table; and all other words indicate variable data values. The Selection Rules and data objects that are used are indicated as ***Si, Pi*** and ***FAi*** , respectively.

Coordination is possible if the select statement returns rows from the Coordination Table. Multiple rows, or device pairs, may exist in the Coordination Table which satisfy the selection rules. In this case the procedural mode is used to implement rule ***S1***.

When coordination fails (i.e. no rows selected from coordination table), selection rule ***S7*** allows the Selection Rule Processor to attempt coordination by using other device types. For example, if fuse device types are being selected as governed by rule ***S11*** and coordination fails, then the procedural mode implements selection rule ***S7***. Thus, rule ***S7*** overrides ***S11*** and forces the Selection Rule Processor to use an alternate select statement which considers recloser or relay type devices. Whenever coordination fails due to an activated selection rule the goal is to insure that all possible device types have been utilized in attempting coordination . This implements a consistency check to avoid coordination failure due to activated rules.

As indicated in Figure 6.15, the Selection Rule Processor uses data from the Protection Objects that are defined in Table 6.7. A Protection Object is linked to every dummy protective device. PO_Flag is initially set to YES and the Selection Rule Processor attempts to coordinate the interconnected circuits using the values of Absolute Maximum and Minimum fault currents that are stored in ***PO1*** and ***PO4***, respectively. These are the

```
SELECT (Backup_Device )
 FROM Coordination Table WHERE
   Primary_Device = Primary Device #                       AND
   Backup_Type = Device Type                               AND
   Backup_Volt_Rating      >= Circuit Voltage              AND
   Backup_Amps_Rating      >= (PO2 * S12 parameter)        AND
   Max_Coord_Amps >= (PO1 * S13 parameter)                 AND
   Min_Coord_Amps >= (PO2 * S9 parameter)                  AND
   Min_Coord_Amps <= PO3                                   AND
   Min_Coord_Amps <= PO4                                   AND
   Min_Coord_Amps <= PO5                                   AND
   Min_Coord_Amps <= PO6
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 6.15. Example SQL Select Statement

fault currents developed by considering all circuit configurations for the interconnected system of circuits. If coordination fails, i.e. SQL Flag is not Success as shown in Figure 6.14, for the Absolute Maximum and Minimum fault currents and all alternate device types have been checked for possible coordination, PO_Flag is set to NO, and Select_Level is reset to zero. For the condition of PO_Flag set at NO, only the Forward Maximum and Forward Minimum fault currents, i.e. ***FA3*** and ***FA6***, respectively, are used when attempting device coordination. Thus, ***FA3*** and ***FA6*** replace ***PO1*** and ***PO4***, respectively, when PO_Flag is changed from YES to NO. The required changes to the SQL Select statement are shown by Figure 6.16. However, if coordination fails again when PO_Flag is set to NO, device coordination is not possible by the Selection Rule Processor. The designer is notified by the Failure of Device Coordination as indicated is Figure 6.14.

All the dummy protective devices at a given protection level of Select_Level are processed as shown in Figure 6.14. If all the devices at a given Select_Level have been processed, the value of Select_Level is incremented, and all devices at that Select_Level are processed. The selection process continues until the Select_Level for the devices being selected equals the value of Max_Level . For a given circuit, the Selection Rule Processor is successful and reaches DONE when all of the dummy protective devices are replaced with actual protective devices.

```
SELECT (Backup_Device)
  FROM Coordination Table WHERE
      Primary_Device = Primary Device #                    AND
      Backup_Type = Device Type                            AND
      Backup_Volt_Rating   >= Circuit voltage              AND
      Backup_Amps_Rating >= (PO2 * S12 parameter)          AND
      Max_Coord_Amps >= (FA3 * S13 parameter)              AND
      Min_Coord_Amps >= (PO2 * S9 parameter)               AND
      Min_Coord_Amps <=  PO3                               AND
      Min_Coord_Amps <=  FA6                               AND
      Min_Coord_Amps <=  PO5                               AND
      Min_Coord_Amps <=  PO6
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 6.16. Example SQL Select Statement for PO_Flag Set to NO

6.8. Key Features Summary of the Expert System

A summary of major features incorporated by the expert system for protection system design include the following --

- The expert system incorporates the key elements and requirements outlined by IEEE in Reference 15 which consist of:

  Data Integration,
  Relational Database Management System, and
  A Graphical User Interface, GUI, that is provided by DANE.

- Data integration is achieved by the relational database system and by the sharing of in-memory created data objects that include:

  Component Objects, and
  Fault Analysis Object,
  Protection Objects,
  Selection Objects.

- The Inference Engine consists of four functions, Fault Analysis, Coordination Rule Processor, Placement Rule Processor and Selection Rule Processor, that dynamically create data for the Knowledge Base .
- Influencing Expert Rules controlled by the designer are associated with three functions as shown below:

Coordination Rule Processor Function	- 13 Rules,
Protection Rule Processor Function	- 8 Rules, and
Selection Rule Processor Function	- 13 Rules.

- The Expert System is programmed using the C language and ESQL statements.

CHAPTER 7

Design Example And Results

7.1. Introduction

An example protection system design is presented using an integrated expert system developed for the DANE engineering workstation. The example problem consists of three interconnected distribution circuits. Dynamic knowledge created by the expert system from the rules and system data is used in the design. System data is presented pertaining to the circuits along with the created dynamic knowledge. The implemented rules dealing with the coordination, placement and selection of protective devices are presented along with all associated parameter values. The final design and results are shown.

The modeling techniques for protective devices were presented in Chapter 5 of this report. In Chapter 6 various aspects were presented concerning the development of the integrated expert system for protection system design, as well as the design rules pertaining to coordination, placement and selection. Chapter 6 also presented the overall expert system design and rule processors. This chapter presents the pertinent data involved in a protection system design using the expert system developed under DANE. The focus for this chapter is on the data -- both data that exists and data that is created and utilized -- and the overall results using the expert protection system design system.

The focus of the expert system is dynamic data, or knowledge, creation via data integration. Dynamic knowledge, as defined here, is dependent upon both existing data that remains fixed and influencing data that is changeable. Equipment data pertaining to conductors, transformers and protective devices are examples of fixed, or static, data; while circuit configurations, rule processors and associated rule parameters are examples of influencing data.

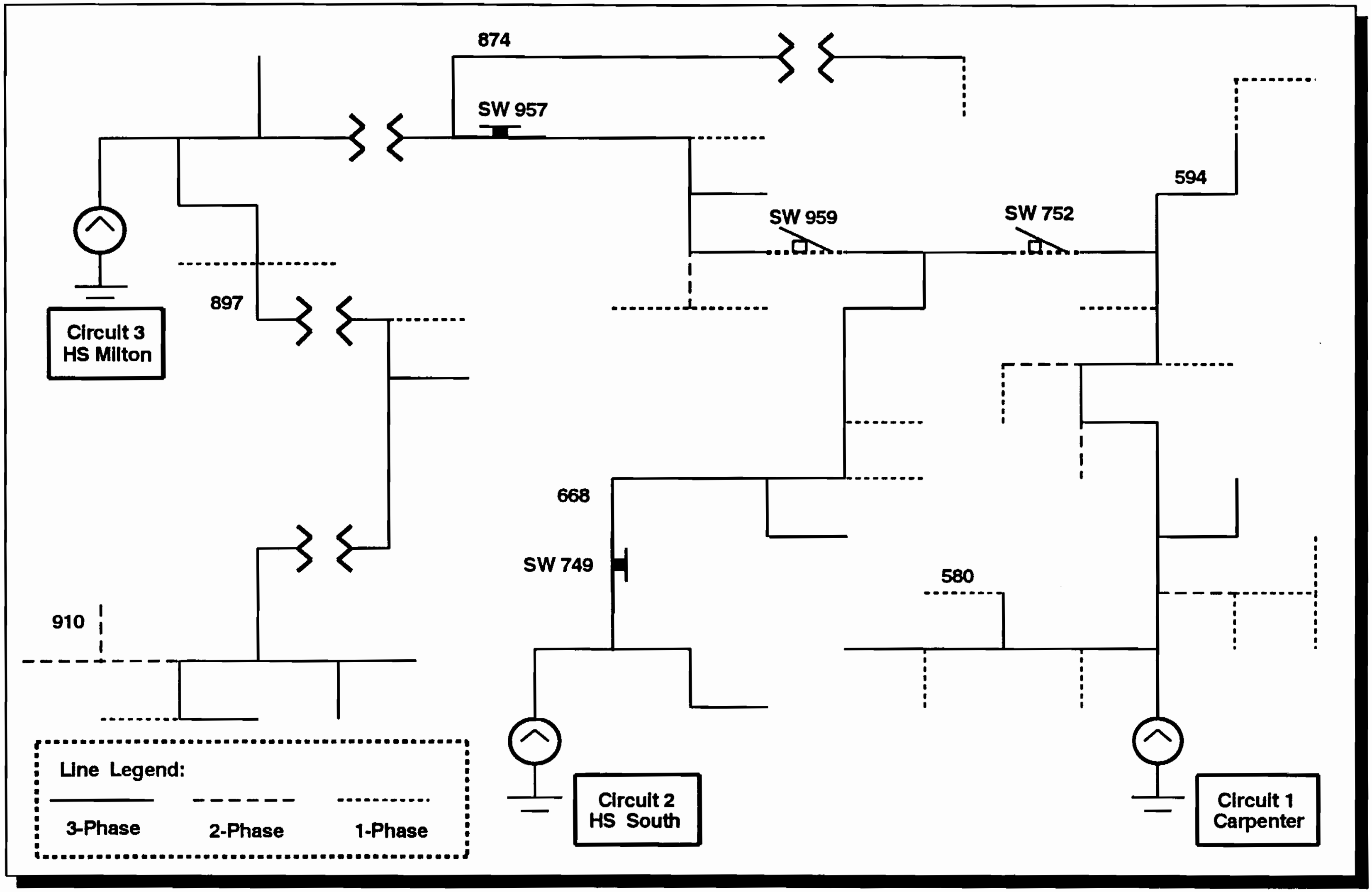

Figure 7.1. Three Interconnected Design Circuits

The expert system utilizes engineering functions, such as fault analysis, power flow, and reconfiguration together with the coordination and placement rule processors to create a dynamic knowledge base from the fixed data. The selection rule processor utilizes the dynamically created knowledge to design a protection system. As such, the knowledge base for the expert system is not a conventionally programmed one using solely rule knowledge bases.

The engineering workstation used for this design example consisted of the following hardware: A 25MHz IBM PS/2 Model 70/386 machine with 8Mb of RAM, 64Kb cache memory and 120 Mb hard disk. The operating system for the software was OS/2 version 1.3.

7.2 Background Circuit Information

An expert system design study is presented involving the protection system for three interconnected distribution circuits. The interconnected circuits are from the Hot Springs Division of Arkansas Power and Light in Hot Springs, Arkansas. Arkansas Power and Light has been intensively involved in working with the engineering workstation developed at Virginia Tech. Over 100 interconnected circuits from the Hot Springs Division have been modeled in the workstation.

The engineering schematics for the three circuits are shown in Figure 7.1. The engineering schematics in Figure 7.1 are not drawn to scale and some circuit components are not shown by the schematics. In particular, the 15 existing capacitor banks located on the circuits are not shown. Figure 7.1 shows substations, lines, switches and transformers.

The three circuits originate from three separate urban 115 - 13.8 KV substations in the area south of Hot Springs, Arkansas and span out to serve rural customers. The three circuits are interconnected by two switches, namely SW 959 and SW 752, as shown in Figure 7.1. The other switches utilized by the design study are shown in Figure 7.1.

The customers supplied by the three circuits consist of 1 industrial , 700 commercial and 4650 residential. The customers served are predominantly rural residential customers. The 1 industrial customer is supplied by Circuit 1 from the Carpenter substation. The commercial customers are located in the urban areas along the three circuits. The three circuits consist of approximately 110 line section components which total about 84 miles of conductors.

For future reference, a table of abbreviations used throughout this chapter are presented in Table 7.1. Table 7.2 presents example line types by circuit location as shown in Figure 7.1.

The remaining chapter sections present data used during the design study. Data concerning the protective devices utilized to build the Coordination Table for the design are presented in the next section. The Placement Rule Processor and associated engineering functions are presented in Section 7.4. The Selection Rule Processor analysis for the circuits and final design results are presented in Section 7.5. Conclusions are presented in Section 7.6.

7.3. Protective Device Data And Coordination Table

The protective device data utilized for the design consisted of 20 fuse, 90 recloser, and 145 relay curves. From these device curves the Coordination Rule Processor built the Coordination Table used by the Selection Rule Processor. The coordination principles and corresponding parameter values that were adopted for the design are shown in Table 7.3. The implemented coordination rules produced approximately 15,000 device coordination pairs. Thus, the Coordination Table built contained 15,000 rows. The minimum coordination range, or ***C13***, was set at 400 amperes.

Table 7.1. Chapter 7 Abbreviation Definitions

Abbreviation	Definition of Symbol
CLI	Circuit Location Index - used to reference a location in a given circuit schematic.
CONF_ID	Configuration Identification for the interconnected circuits
MAX IR	Maximum Interrupting Rating for a protective device
MIN PU	Minimum Pickup for a protective device
GRD	Ground

Table 7.2. Example Line Types Shown in Figure 7.1

CLI	Line Types and Construction Description
910	#4 ACSR, 2-Phase, Cross Arm Construction
897	795 AL, 3-Phase, Vertical Construction
874	336 ACSR, 3-Phase, Vertical Construction
668	336 ACSR, 3-Phase, Cross Arm Construction
594	#4 ACSR, 3-Phase, Cross Arm Construction
580	#6 CU, 1-Phase, Vertical Construction

Table 7.3. Implemented Coordination Rules

Rule Label	Fault Type	Primary Curve	Backup Curve	Parameter
C1	P	Fuse Clearing	Fuse Melting	75%
C2	M	Fuse Melting	Fast Recloser Trip	75%
C3	P	Fuse Clearing	Delayed Recloser Trip	95%
C4	P	Fuse Clearing	Relay Trip	95%
C5	P	Delayed Recloser Trip	Fuse Melting	80%
C6	M	Fast Recloser Trip	Fast Recloser Trip	95%
C7	P	Delayed Recloser Trip	Delayed Recloser Trip	65%
C8	P	Delayed Recloser Trip	Relay Trip	95%
C9	P	Relay Trip	Fuse Melting	75%
C10	P	Relay Trip	Fast Recloser Trip	95%
C11	P	Relay Trip	Delayed Recloser Trip	90%
C12	P	Relay Trip	Relay Trip	95%

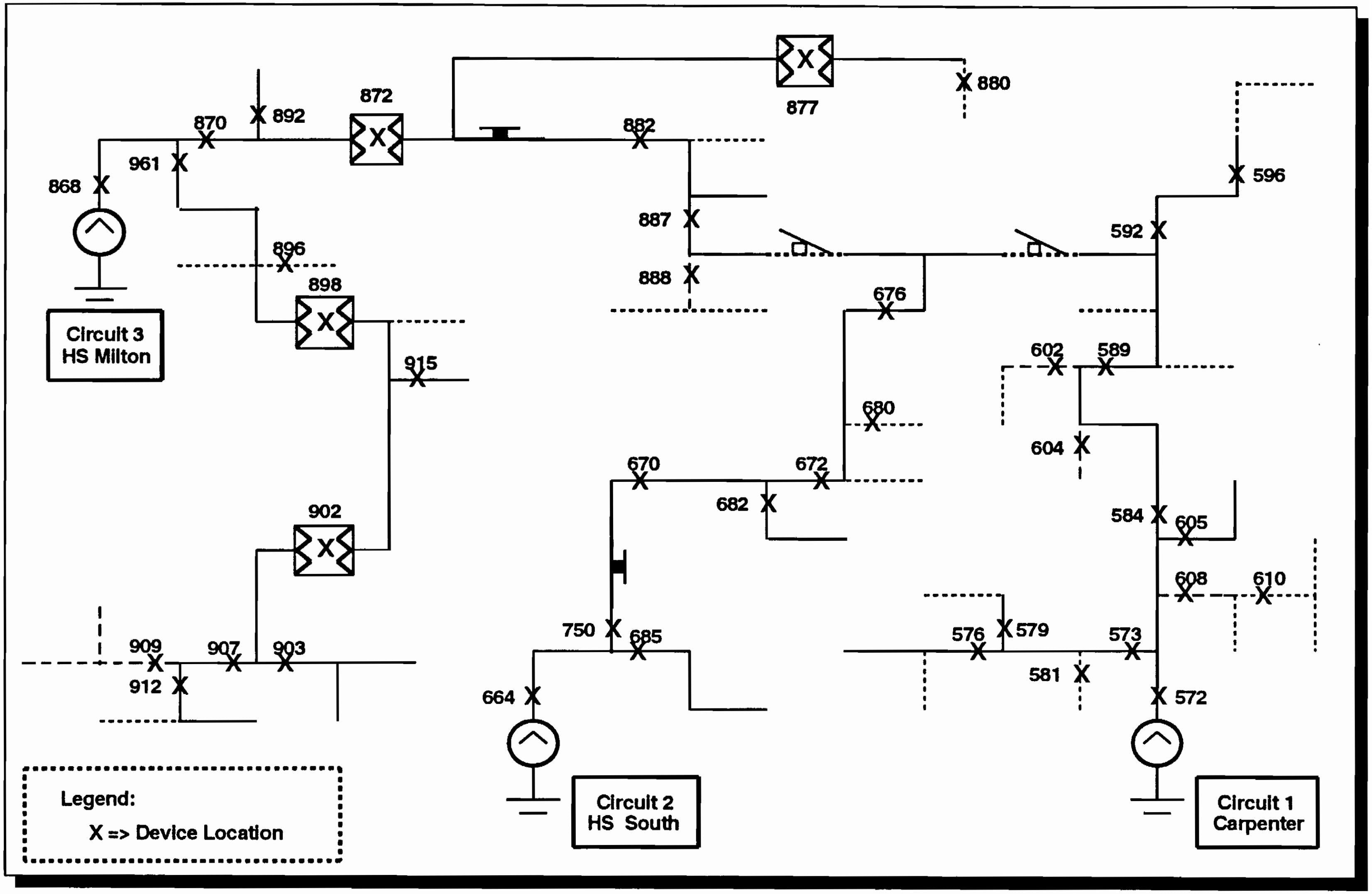

Figure 7.2. Placement Locations for Three Circuits

7.4. Placement Rule Processor Data

The Placement Rule Processor utilizes workstation analysis functions which include fault analysis, power flow, and switching configurations. These analysis functions have been checked against those used by Arkansas Power and Light, **DFA**[53].

For a given set of interconnected circuits, the Placement Rule Processor performs switching operations based on the switching configurations. The switching configurations used in the design example are shown in Table 7.4, where only those switches that change position are shown. In Table 7.4, the CONF_ID of -1 represents the normal, or base, operating configuration for the circuits. The base configuration determines the normal direction of current flow through each component. For each configuration, fault analysis calculates fault currents, and power flow determines the load current at peak circuit loading for each component of the interconnected circuits involved in the design.

The data from fault analysis and power flow are used to update individual component values. The current values of maximum fault, maximum load, minimum phase fault, minimum fault and equipment ratings are examined for each component as well as the direction of current flow. For each configuration, the Placement Rule Processor determines if the existing values for each component need to be updated. For example, if a component's value for maximum load amperes is set at 200 from previous configurations analyzed and power flow yields a value of 245 for the present configuration of the circuits, then placement sets the component value for maximum load amperes at 245. Thus, after all configurations have been analyzed the Placement Rule Processor has determined at each component the appropriate values, either a maximum or minimum, that a particular component may experience for the possible switching configurations defined by the designer.

After all switching configurations have been analyzed, the Placement Rule Processor must use designer activated placement rules together with data from fault analysis and power flow to dynamically create protection objects which are utilized by the Selection Rule Processor. The placement rules used in the design along with the associated parameters are listed in Table 7.5. A more detailed description of the placement rules is provided in Chapter 6 at Section 6.4.2 of this report .

The Placement Rule Processor uses component data and placement rules to determine protective device locations. After the placement processor has placed protective devices, the designer is able to remove or add protective device locations. Figure 7.2 denotes the locations chosen for protective devices with an "X". Placement of devices before and after transformers is indicated by placing an "X" within the transformer symbol. The final step for the Placement Rule Processor is the dynamic creation of protection design objects based on the chosen protective device locations.

Values for members of the protection system design objects associated with Circuit 1 are given in Table 7.6. The CLI column represents the index for protective device locations of Circuit 1 as shown by Figure 7.2 . A brief definition of the columns is as follows (refer to Table 6.2 in Chapter 6 for additional information):

PO1 = Maximum fault current that device must interrupt as either a primary or backup device.

PO2 = Maximum load or cold load inrush current through the device.

PO3 = Minimum phase fault current that device must sense as a primary or backup device.

PO4 = Minimum fault current that device must sense as either a primary or backup device.

PO5 = Minimum equipment ratings of all downstream components that device must protect as either a primary or backup device.

PO6 = Minimum downstream amperes, either equipment ratings or minimum fault, that must be protected by the device.

Table 7.4. Switching Patterns for Circuits

CONF_ID	SW 752	SW 749	SW 959	SW 957
-1	Opened	Closed	Opened	Closed
1	Opened	Closed	Closed	Opened
2	Closed	Opened	Opened	Closed

Table 7.5. Implemented Placement Rules

Rule Label	Parameter	Rule Description & Engineering Analysis Functions
P1	--	A device is located at the start of each circuit.
P2	--	Devices are located at both the primary and secondary sides of all transformers.
P3	--	Placement of devices back-to-back is not allowed.
P4	1	If the total length of the downstream lateral exceeds the value of this parameter, then a locate a device at the start of the lateral.
P5	26	If the ratio of the maximum fault current to the minimum fault current for a potential new zone exceeds the value of this parameter, then a place a device at the circuit location being evaluated.
P6	750	If the number of customers in a potential new zone exceeds the value of this parameter, then a place a device at the circuit location.
P8	1	For a feeder tie-line, the number of devices to be evenly distributed over the length of the tie-line is set at the value of this parameter.

Table 7.6. Protection Objects for Circuit 1

CLI	***PO1***	***PO2***	***PO3***	***PO4***	***PO5***	***PO6***
572	10,536	645	4,060	169	725	107
608	3,361	70	2,820	170	107	107
610	1,332	62	170	170	115	107
605	2,066	28	834	169	107	107
584	2,875	456	1,615	170	725	107
604	1,596	15	1,140	164	107	107
602	1,395	30	150	150	107	107
589	2,115	394	1,147	147	725	107
592	1,732	43	637	124	430	107
596	659	20	124	124	115	107
573	5,107	108	4,148	179	402	107
581	1,618	18	181	181	107	107
576	3,733	42	2,370	179	402	107
579	3,430	30	183	183	201	107

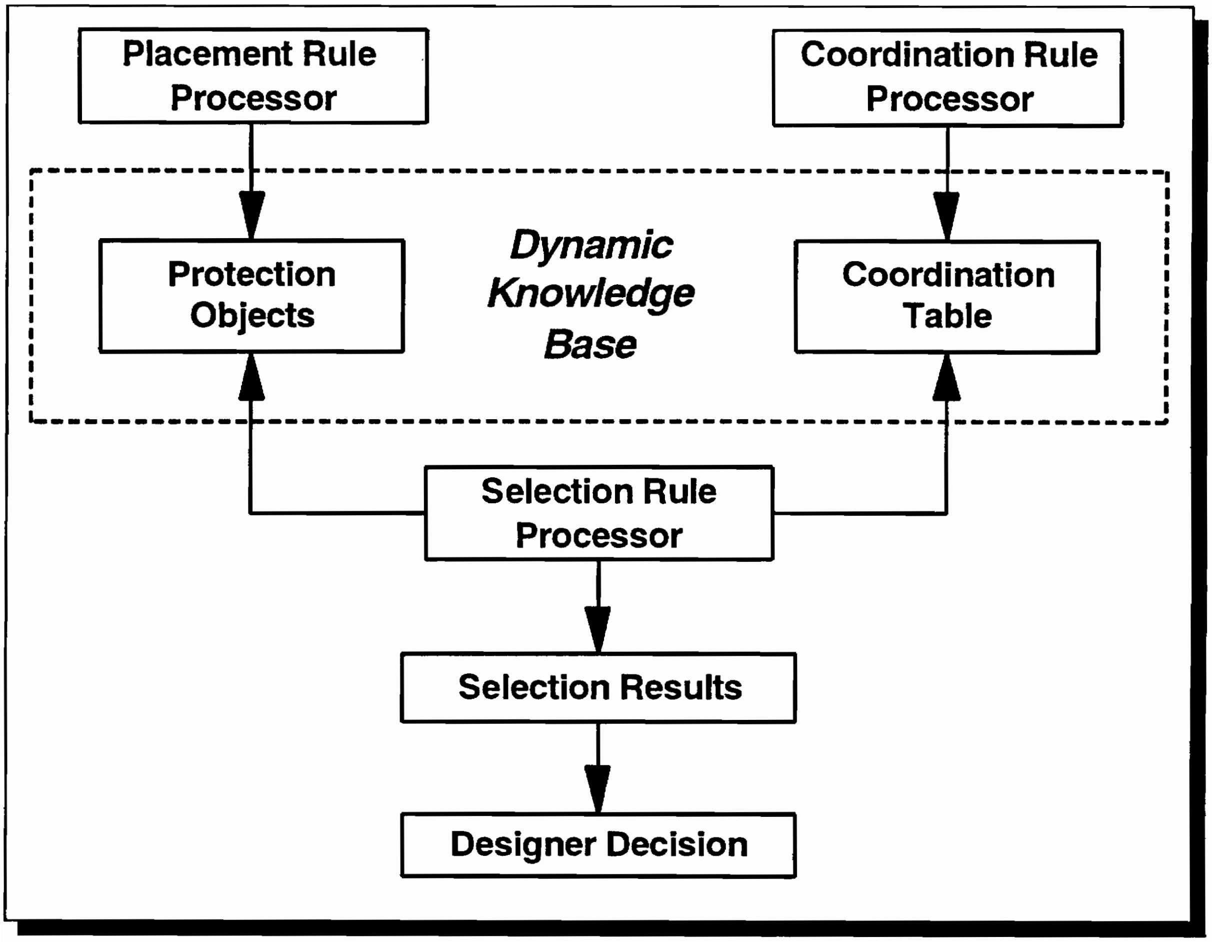

Figure 7.3. Dynamic Knowledge Base for Selection Processor

```
SELECT (Backup_Device)
  FROM Coordination Table WHERE
     Primary_Device = Primary Device # @ 596        AND
     Backup_Type  = Fuse                            AND
     Backup_Volt_Rating   >= 13800.0                AND
     Backup_Amps_Rating >= 43 * 1.2                 AND
     Max_Coord_Amps >= 1732 * 1.5                   AND
     Min_Coord_Amps >=  43 * 1.75                   AND
     Min_Coord_Amps <=  124                         AND
     Min_Coord_Amps <=  115                         AND
     Min_Coord_Amps <=  107
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 7.4. SQL Fuse - Fuse Select Statement

7.5. Selection Rule Processor

The device locations in the interconnected circuits shown in Figure 7. 2 are analyzed by the Selection Rule Processor. Table 7.7 shows the selection rules and their associated parameters used in the design (refer to Table 6.3 in Chapter 6 for additional information).

As illustrated in Figure 7.3, the Selection Rule Processor uses data from the Protection Objects together with the Coordination Table to interactively Select Coordinated protective devices. The Protection Objects associated with each device location determine the operating conditions that must be satisfied by the selected device from the Coordination Table. The Selection Processor uses SQL Select statements which query the Coordination Table. Four specific Select statements used for Circuit 1 device locations are shown in Figures 7.4, 7.5, 7.6 and 7.7.

Figure 7.4 shows the Select statement used to perform a Backup Fuse - Primary Fuse selection for CLI *592* and CLI *596*. At this juncture in the design, at CLI *596* a fuse has already been selected and the device at CLI *592* is being selected from the Coordination Table. Thus, the device at CLI *592* must serve as the Backup device for CLI *596*.

The SQL select statement used in Figure 7.4 produced a coordinating backup fuse device from the coordination table. Preceding in a similar manner toward the substation the Selection Rule Processor must select a device at CLI *589*.

The SQL select statement shown in Figure 7.4 has four qualifiers on the value for *Min_Coord_Amps*. However, if the value qualifier for *Min_Coord_Amps* associated with (***PO2* * *S9*** parameter) exceeds the value qualifier for *Min_Coord_Amps* associated with ***PO6*** then the Selection Rule Processor uses a "Ground Pickup" and sets all "Phase" protective devices based on the value of ***PO3***. This occurs when the peak load current is such that the "Phase" protective device cannot be set to detect the minimum fault current as the peak load current would be detected as a fault. Ground pickups are available on reclosers and relays.

Table 7.7. Implemented Selection Rules

Rule Label	Parameter	Rule Description & Engineering Analysis Functions
S1	No	Select the fastest operating device.
S2	No	The voltage rating of device at the circuit location.
S3	No	Reclosers are selected at all three-phase locations.
S4	No	Pickup less than the minimum of primary and backup fault currents
S5	No	Pickup less than the minimum of primary and backup equipment ratings
S6	No	Use recloser to protect for transient faults.
S7	No	Try all devices if coordination fails.
S8	No	Use recloser ground trip when coordination fails or when (***PO2*** * ***S9*** parameter) exceeds ***P06***
S9	1.75	Pickup scaling factor for load current
S10	0	Breakers at start of circuits
S11	3	Number of fuses in series
S12	1.2	The continuous current rating scaling factor for devices.
S13	1.5	The interrupting rating scaling factor for devices.

```
SELECT (Backup_Device)
 FROM Coordination Table WHERE
   Primary_Device = Primary Device # @ 592          AND
   Backup_Type = Recloser                           AND
   Backup_Volt_Rating  >= 13800.0                   AND
   Backup_Amps_Rating >=   394 * 1.2                AND
   Max_Coord_Amps >= 2115 * 1.5                     AND
   Min_Coord_Amps >=  394 * 1.75                    AND
   Min_Coord_Amps <=  1147                          AND
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 7.5. SQL Recloser - Fuse "Phase" Select Statement

Figure 7.5 shows the Select statement used to perform a Backup Recloser - Primary Fuse selection. CLI *592* had a fuse selected for it, and a recloser device is being selected at CLI *589* from the Coordination Table. Note that at CLI *589*, ***PO2*** is such that the "Phase" protective device must be set above ***PO6***. Therefore, a ground pickup must be used to protect for ***PO6***.

```
SELECT (Backup_Device)
 FROM Coordination Table WHERE
   Backup_Device  = Backup Device # @ 589       AND
   Primary_Device = Primary Device # @ 592      AND
   Backup_Type = Recloser                       AND
   Min_Coord_Amps <= 107                        AND
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 7.6. SQL Recloser - Fuse "Ground Pickup" Select Statement

The SQL select statement used in Figure 7.5 produced a coordinating backup recloser device that had available ground pickups from the coordination table. For the recloser selected, the Selection Rule Processor then used a SQL select statement, as illustrated in Figure 7.6, to select the ground pickup for the recloser at CLI *589*. At this point the Selection Rule Processor knows that all protective device locations upstream will have to utilize ground pickups to sense and protect minimum fault currents.

```
SELECT (Backup_Device)
  FROM Coordination Table WHERE
    Primary_Device = Primary Device # @ 589          OR
    Primary_Device = Primary Device # @ 602          OR
    Primary_Device = Primary Device # @ 604          AND
    Backup_Type = Recloser                           AND
    Backup_Volt_Rating   >= 13800.0                  AND
    Backup_Amps_Rating >=  456 * 1.2                 AND
    Max_Coord_Amps >= 2875 * 1.5                     AND
    Min_Coord_Amps >=  456 * 1.75                    AND
    Min_Coord_Amps <=  1615                          AND
ORDER_BY Backup_Amps_Rating, Max_Time_Diff
```

Figure 7.7. SQL Backup Recloser - Recloser/Fuse Select Statement

Preceding in a similar manner toward the substation the Selection Rule Processor must select a device at CLI *584*. Figure 7.7 shows the Select statement used to perform a Backup Recloser - Primary Recloser/Fuse selection. CLI *589* had a recloser selected for it, and a "Phase" recloser device is being selected at CLI *584* from the Coordination Table. However, at CLI *584* the recloser device must serve as backup for fuses that have been selected at CLI *602* and CLI *604*. Thus, the recloser must coordinate with 3 downstream devices. The Select statement shown in Figure 7.7 uses an *OR* condition to reflect this requirement on the recloser device.

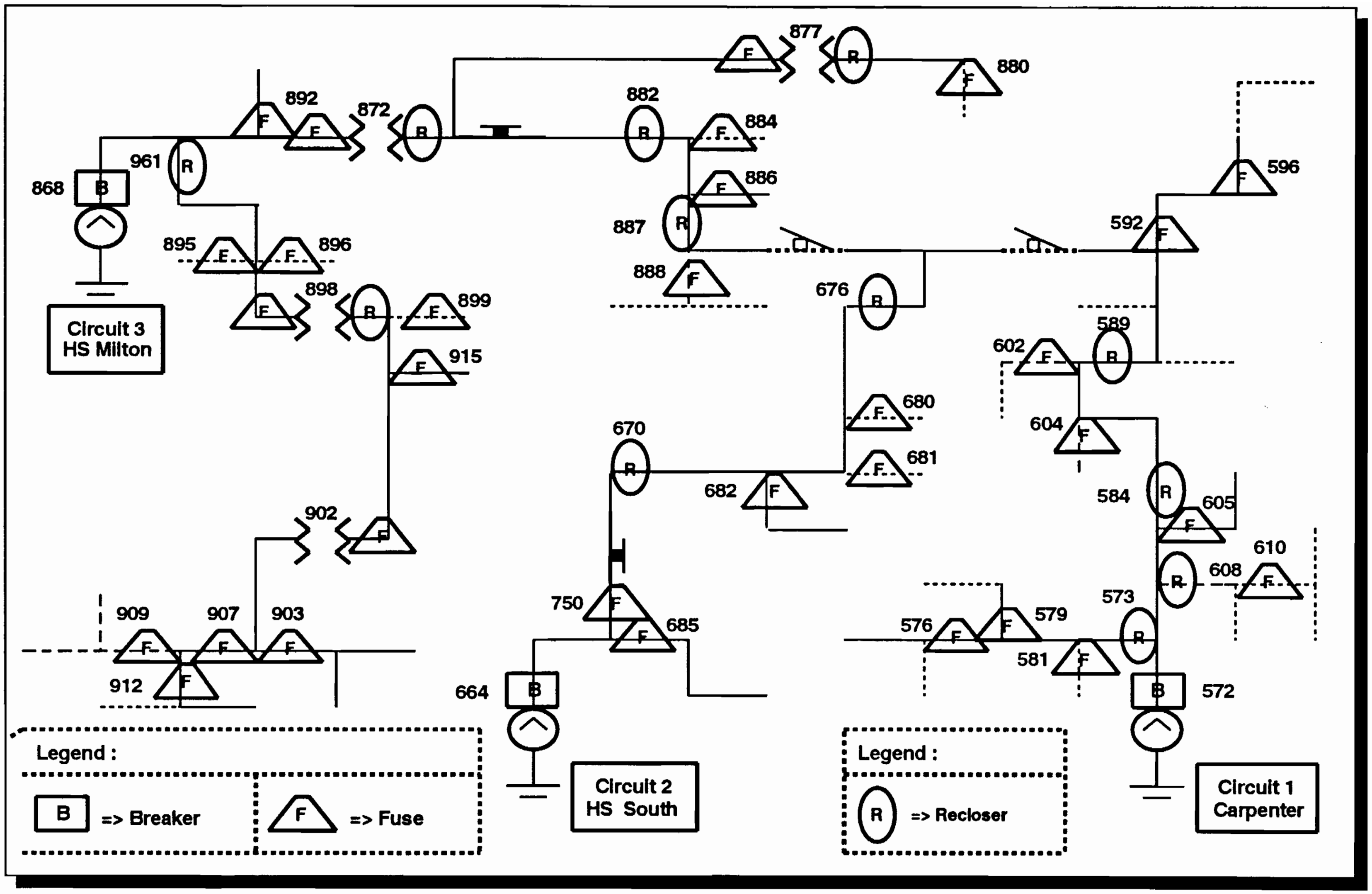

Figure 7.8. Final Protection System Design For The Circuits

In a similar fashion, the Selection Rule Processor analyzes each Protective Object that is associated with each device location. The Selection Rule Processor then uses the appropriate SQL Select statement to query the Coordination Table. For this example the Selection Rule Processor was able to design a coordinated protection scheme from the Coordination Table for the given switching configurations of the circuits.

The final protection system design for the interconnected circuits is shown in Figure 7.7. Table 7.8 contains relevant data concerning those protective devices that were selected for Circuit 1 in the final design.

7.6. Conclusions

Chapter 6 of this report presented an expert system for protection system design applications. In Chapter 7 of this report a specific protection system design for three interconnected circuits is presented using the developed expert system.

The expert system is able to fully integrate the pertinent data involved in the protection system design for interconnected radial distribution circuits. The designer is able to concentrate on the more relevant issues of the overall design, and delegate the management of large quantities of data to the computer. While it may be an expert system, the designer must be familiar with the numerous aspects entailed in designing protection systems. The intent behind the developed expert system is as a planning tool. A tool to improve the productivity of the protection engineer, not a replacement for the engineer.

Table 7.8. Protective Devices Selected for Circuit 1

CLI	Device Type	Amps Rating	MAX IR	MIN PU	GRD PU
572	BREAKER	1,500	20,000	600	120
608	RECLOSER	100	6,000	200	65
610	FUSE	75	6,000	100	--
605	FUSE	75	6,000	100	--
584	RECLOSER	560	12,000	1,120	65
604	FUSE	60	5,000	80	--
602	FUSE	75	6,000	100	--
589	RECLOSER	560	10,000	750	65
592	FUSE	75	6,000	100	--
596	FUSE	60	5,500	80	--
573	RECLOSER	140	8,400	280	65
581	FUSE	75	6,000	100	--
576	FUSE	90	6,500	130	--
579	FUSE	75	6,000	100	--

CHAPTER 8

Conclusions and Recommendations

8.1 Contributions

The foundation for this research was based on an IEEE Committee Report concerning the need for an integrated software system for protection system design that is clearly stated in Reference 15. Thus, one goal of the research was the design of an expert system that fulfills, as much as possible, the general requirements and guidelines concerning protection system design as specified by [15]. The stated general requirements as specified by the IEEE Committee are as follows:

1) Integrated software system approach,
2) Data stored in a Relation Database Management System, and
3) Graphical User Interface.

This research work has built upon and expanded the research work of Maghdan in protection system design [16]. However, the research has addressed three critical issues that were not addressed by Maghdan's work which are given below.

1) The impact of the multiple circuit configurations when considering an interconnected system of circuits.
2) A method for modeling protective devices that reduces data storage.
3) The impact of cogeneration on the system of interconnected circuits during fault conditions.

This research has implemented a rule based expert system for protection system design. The intent was to provide the architectural structure for a software system that provided the protection system design engineer with the capabilities as outlined by IEEE.

The expert system is a design tool not a replacement for the engineer. The major points of this research were presented to the IEEE PES at the 1993 Summer Meeting [53] and [54].

The main contributions of the research work are summarized below:

- The expert system is an integrated software system . The four functions in the Inference Engine share data and also produce knowledge for the Knowledge Base. The Rule Base of the expert system is relatively small and simple.
- The software system fulfills the three general requirements as outlined by IEEE in Reference 15.
- The expert system is able to handle multi-directional current flows for a system of interconnected radial circuits.
- The effects of cogeneration during fault conditions is taken into consideration by the expert system.
- The protective device model developed for the research is able to significantly reduce the amount of required data storage by utilizing two database tables, the Curve and Device Tables, to store the protective device data.
- The method of implementation of the expert system using C and ESQL is new approach in the area.
- Since the protective device data is compacted it can be loaded into computer memory by DANE, and no hard-disk accesses are required to retrieve this data. Thus, software applications that utilize protective devices execute faster.

- The designer can evaluate alternative design schemes that utilize various combinations of protective devices by adding and/or removing devices from the Protective Device and Curve Tables.

8.2. Future Recommendations

Future work pertaining to this research may wish to consider the following areas of suggestions:

- The modeling of TCC protective device curves as equations that parallels the method presented in Reference 55. This approach should reduce the amount of required data storage. In the future, the TCC data may be more readily available from manufacturers in this form.
- An expansion of the Rule Bases, that is based on a conducted survey involving protection system design engineers from a broad base of electrical utilities, may lead to more standardized practices in protection system design.
- Methods to address the building the Coordination Table, that reduce the data storage size requirements.
- The effects of permanent faults on the remaining unfaulted portions of the system when the fault is cleared by a protective device. If a single phase lateral section has a fault cleared, will the unfaulted portion of the circuit be so severely unbalanced that other protective devices begin to sense unbalanced load flows as faults? What methods are needed to correct this situation? The solution to this problem may imply smaller protection zones, more protective devices in the circuit , or designer programmable "smart" protective devices.

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