PLACEMENT AND COORDINATION OF OVERCURRENT RELAYS IN POWER DISTRIBUTION SYSTEMS

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in System Engineering and Operations Research)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation entitled **"PLACEMENT AND COORDINATION OF OVERCURRENT RELAYS IN POWER DISTRIBUTION SYSTEMS"** in the partial fulfillment of the requirement for the award of the degree of **Master of technology in Electrical Engineering** with specialization in **System Engineering and Operation Research**, submitted in the **Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee,** is an authentic record of my own work carried out during July 2005 to June 2006 under the supervision of **Prof. Hari Om Gupta**, Department of Electrical Engineering, IIT Roorkee, Roorkee.

I have not submitted the matter embodied in this dissertation for award of any other degree.

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Date: 30/6/2006
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CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge.

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ABSTRACT

Directionally overcurrent relays are popularly used for the primary protection of distribution circuits. Directionally overcurrent relays are placed strategically through out the system and determination of settings of these relays is the core issue to properly coordinate them.

In this dissertation work, the relay coordination problem is solved in non-linear environment after transforming it into a parameter optimization problem. The problem has been solved in non-linear environment by the Steepest Descent (Gradient) method with exterior penalty approach. A pre-processing algorithm is presented which helps in identifying infeasible and redundant constraints, and thereby reducing the complexity of the problem.

A new objective function is used, which significantly improves the selectivity and reliability of the protection system. By modifying the objective function to sum of minimization of constraint violations in place of the conventional objective function, it is expected that better settings for the relays will be obtained.

A decomposition algorithm is presented to tackle the coordination problem of large power systems. New algorithms are developed for formulating the coordination problem and used for solving the coordination problems of a 6-bus and IEEE 14-bus test systems.

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LIST OF VARIABLES

The list of variables used in this dissertation work is listed below. Any minor departure from this list and specially used symbols are explained in the text itself.

Principal Symbols

CTI : Coordination time interval

F : Performance or Objective function

f : Function

TDS : Time Dial Setting

PS : Plug Setting

I_m : Current for a fault at the far bus under maximum generation conditions.

I_s : Instantaneous Current setting

I_p : Pickup Current Setting

K_1, K_2, K_3 : Constants of the relay to be simulated

T_{ijk} : Operation time of relay i of zone j for a fault in zone k

I_{pmin} : Lower limit of I_p

I_{pmax} : Upper limit of I_p

TDS_{min} : Lower limit of TDS

TDS_{max} : Upper limit of TDS

T_i : Operating time of the delay unit of a relay i

T_{imax} : Maximum time of operation allowed for relay i

T_{imin} : Minimum time of operation allowed for relay i

Chapter 1

INTRODUCTION

1.1 OVERVIEW

Protective relaying is an important part of electric power system. Its main function is to cause the prompt removal of any element from service in the power system when it starts to operate in an abnormal fashion that might cause damage or interfere with the effective operation of the rest of the system. Hence it is quite unnecessary during normal operation of the system, but very important during abnormal conditions. The relaying equipment is aided in its task by circuit breakers which are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment.

Protective relays are placed strategically throughout the power systems and operate in a coordinated manner. The process of determining the relay settings in such a way that all the B/ P relay pairs operate as planned is known as the relay coordination. The coordinated or selective operation of the relays is a function of power system topology, relay characteristics and protection philosophy. The problem of coordinating protective relays in electric power systems consists of selecting their suitable settings such that their fundamental protective function is met under the requirements of Sensitivity, Selectivity, Reliability and Speed. These are described below:

1. Sensitivity - a variety of fault conditions must be detected by the appropriate relays.
2. Selectivity - the relays located closer to the fault should have priority of operation.
3. Reliability - if a primary relay fails, its backup relay should operate.
4. Speed - the operation of relay should be as fast as possible and must occur only in the presence of abnormal conditions or faults.

Lines are protected by overcurrent, distance and pilot relaying systems depending upon requirements. Directional overcurrent relaying is the simplest and the quickest to need readjustment as the system condition changes. Directional overcurrent relays act as secondary to the primary distance relays. It is also generally used for phase and ground-fault protection for distribution circuits and for primary ground fault protection on most transmission lines where distance relays are used for phase faults. It has been very difficult to coordinate the Directional overcurrent relays on transmission lines in power networks. Each relay must be set so that it not only recognizes faults in its zone of protection, known as primary protection zone, and acts very quickly, but also operates discriminately in a proper time sequence with the relays on neighboring lines. By discrimination it means that the relay should recognize a fault outside its zone of protection and operate sufficiently slower than other relays which are meant for primary protection for this fault. Therefore the operating time for each relay is calculated and compared under different fault conditions. If necessary, new settings must be computed to obtain proper coordination with the relays on neighboring lines. Earlier the relay settings were computed manually. This used to be a huge burden on protection engineers, consuming their time on long and laborious calculations. The relay settings are arrived by taking into consideration various network contingencies and system loading which may be reasonably expected up to the new anticipated change in the settings. The resulting settings are very conservative with a huge safety margins thus substantially limiting the relay sensitivity and operating range. The introduction of computer aided relay coordination has increased the operational performance.

Traditionally, the protective relays have consisted of electromechanical or solid state relays which are analog type devices. As the digital equivalents of these relays have been developed, many new concepts, schemes and algorithms have come up and opened doors for adaptive protection. Basically the protection philosophy is divided into two parts; Adaptive protection and Conventional interactive solution philosophy. By adaptive protection we mean that the protective relays have to

respond to actual conditions of the power system and calculate the coordinated settings in an online manner, thereby removing the burden of protection engineers.
A protective relay does not anticipate or prevent the occurrence of a fault, but takes an appropriate action only after the fault has been occurred. One of the important drawbacks in protection philosophy is the concept of pre-determinism. Though the relays are set by taking into consideration all possible network contingencies, there can be some conditions which cannot be incorporated like sympathy trips etc.

In the traditional interactive solution philosophy the engineer runs different cases for distinct faults and configurations until an acceptable solution is reached. However the solution obtained by these interactive algorithms is not optimal in any strict sense, but simply the best of tried possible solutions.

A great deal of effort has been devoted to the automation of the solution of the coordination problem of directional overcurrent relays in power systems.

The problem of coordinating directional overcurrent relays in power systems is stated and solved in the framework of optimization theory. This approach determines the optimal solution to this coordination problem in a cost-effective and efficient way, by stating the problem as a parameter optimization problem and solving it using different optimization techniques.

1.2 LITERATURE REVIEW

The first attempt to solve the coordination problem using computers dates to early sixties. Since then research work has been growing in the area and a number of automated coordination algorithms using various methods have developed. Traditional Trial and Error, Curve fitting and graph theoretical methods as well as optimization methods have been tried by various researchers.

This literature review traces the advancements in protection philosophy since *Urdaneta et al.* [1] proposed a method which uses parameter optimization technique to coordinate the directional overcurrent relays in the interconnected power system.

They have formulated the problem as an extended minmax problem with fixed network configuration and with multiple network configurations.

The papers which first highlighted the concept of adaptive protection came in later part of the year 1988. *Horowitz et al.* [28] defined the adaptive protection in general terms and highlighted specific applications which could be implemented using the newly developed protection philosophy. The treatment of paper is purely conceptual. They have mentioned the adaptive relay setting as a possible application for implementing the coordination philosophy in the general framework of adaptive protection. At the same time *Rockfeller et al.* [3] also presented their ideas about adaptive relaying. *Shah et al.* [2] conducted a feasibility study for adaptive distribution protection system using computer overcurrent relaying concept. They showed that if adaptive distribution concepts are implemented, the benefits would be numerous.

H.Zeienldin et al. have proposed a novel problem formulation for directional overcurrent relay coordination. In this paper they formulated the coordination problem as a mixed integer programming problem taking into consideration, the discrete nature of plug setting (PS).

Hossein Askarian Abyaneh et al. [9] have proposed a new approach for coordination of overcurrent relays in interconnected systems. The proposed method is based only on constraints. Minimization is inherently included by setting the time dials to minimum and increasing their values gradually.

Urdaneta et al. [5,6] have proposed methodologies that takes care of dynamic changes in network topology and consider definite time backup relaying.

1.3 AUTHOR'S CONTRIBUTION

The objective of this dissertation is to develop a new method which can take into account the non-linear nature of directional overcurrent relay coordination. In this dissertation work, the relay coordination problem is solved in non-linear environment.

The author's contribution in this area of research is summarized as follows: The coordination problem is formulated as a parameter optimization problem. A preprocessing algorithm has been developed to exclude redundant and infeasible constraints and reduce the complexity of the problem which helps in finding a feasible solution. A number of variations in the coordination problem are considered.

Various algorithms are developed to systematically perform the coordination process. To solve the directional overcurrent relay coordination of large power transmission systems, an efficient network decomposition algorithm is developed wherein a large power network is decomposed into a number of sub-networks called blocks. It is performed by identifying boundary buses, branches and relays. The blocks are analyzed sequentially and the boundary data table is updated during the solution process. It is observed that larger the number of blocks lesser is the overall execution time needed to solve the problem. This method is very efficient as far as the memory requirements and process speed are concerned. It is established that by using network decomposition algorithm, a better quality of coordination can be achieved rather than considering system as a whole.

1.4 ORGANIZATION OF DISSERTATION REPORT

Chapter 1 presents an overview of the relay coordination problem and a brief review of the literature on the subject area that has been referred to carry out this dissertation work.

Necessary literature review is also presented in the respective chapters in order to have better insight into the basics behind the algorithms presented.

Chapter 2 presents the relay coordination problem as a parameter optimization problem.

Chapter 3 deals with preprocessing work performed in the dissertation work wherein the infeasible and redundant constraints are eliminated to a maximum extent in order to reduce the complexity of the problem.

Chapter 4 presents the necessary algorithms developed during the work and the results from the same. A new methodology [17] is described in which the objective function is modified in order to achieve better quality of coordination.

Chapter 5 deals with decomposition method used in this work to perform the relay coordination. An algorithm is presented and applied to find the solution of relay coordination problem of IEEE 14-bus test power system.

Finally, conclusions of the work are presented. Appendixes and list of references are enclosed at the end.

Appendix I presents the details of 6-bus and IEEE 14-bus test power systems.

Appendix II gives the algorithm of the used non-linear method (Steepest Descent method and Exterior Penalty function method) to solve the relay coordination problem.

Chapter 2

RELAY COORDINATION AS PARAMETER OPTIMIZATION PROBLEM

The use of optimization techniques in solving the relay coordination problem suggested in 1988 [1] was a revolutionary step. It has greatly simplified the relay coordination philosophy.

In [1], the coordination problem was formulated as extended min-max optimization problem and some possible solution methods had been suggested which could solve the problem in an effective way. Their treatment of the subject is fairly general. Both cases; involving the fixed network configurations with several perturbations and the multiple network configurations with several perturbations have been studied by them. Different decomposition techniques have also been presented by them to speed up and simplify the solution techniques.

2.1 RELAY COORDINATION

The relay coordination is a system-wide phenomenon and involves all the relays in the system. A relay operates as primary relay for a fault in its zone of protection and as a backup relay for a fault which is outside its zone of protection. Since there are many interconnections in a realistic power system, therefore, there are many backup/primary (*B/ P*) relationships between different relays. The time lag between the operations of a primary and its backup relays is known as a coordination time interval (*CTI*).

The process of determining the relay settings in such a way that all the B/P relay pairs operate as planned is known as the relay coordination.

A directional overcurrent relay has two main units---

Instantaneous unit operates without any intentional time delay when a current is above the threshold value. This threshold value of current is known as the instantaneous current setting. This setting of the relay provides the primary protection of the lines i.e. the relay operates when a fault occurs in its primary protection zone and does not operate for faults outside this zone. The instantaneous current setting is selected in such a way that the relay provides protection for as large portion of line as possible and does not operate for faults which may occur else where in the system. This setting is calculated as:

$$I_s=1.3*I_m \qquad 2.1$$

Where I_m is the current for a fault at the far bus under maximum generation conditions.

The second unit of directional overcurrent relay is the time delay unit. This unit operates at the occurrence of fault with an intentional time delay. The time delay is adjustable and depends upon the coordination philosophy adopted. This unit is used for currents which are below the instantaneous current setting but exceed the normal flow due to a fault. Two settings are associated with this Unit – the pickup current value (I_p), and the time dial setting (*TDS*). The pickup current value is the minimum current value for which relay operates. The time dial setting defines operation time (T) of the device for each current value and is normally given as a curve T v/s. M, where $M=I/I_p$, I being the relay current.

In general, overcurrent relay respond to a characteristic function of the type,

$$T=f(TDS,I_p,I) \qquad 2.2$$

This can be approximated as under:

$$T=K_1\frac{TDS}{\left[\left(\frac{I}{I_P}\right)^{K_2}+K_3\right]} \qquad 2.3$$

The value for K_1 is 0.14, K_2 is 0.02 and K_3 is -1.0.

The calculation of *TDS* and I_p is the essence of the directional overcurrent relay study. In general directional overcurrent relays allow for continuous time dial settings but discrete pickup current settings. Due to advancement in technology now-a-days, digital relays allows for continuous variation for pickup current settings also.

2.2 STATEMENT OF THE PROBLEM

The coordination problem of protective relays in power systems is stated as an optimization problem of the following general form

$$\underset{s \in S}{Min} \; [z(s,p)] \qquad 2.4$$

where z represents a suitable performance index, s represents the protective device settings, S is the set of permissible settings and p represents the perturbations or fault conditions. The coordination problem becomes more complex when the number of perturbations increases. The performance index must reflect the desired operation of the relay. The desired operation is that the time required to remove the faulty portion of the system upon the occurrence of fault should be minimum. This criterion forces for minimum relay operation time. The problem is more precisely stated as follows:

$$\min \sum_i \sum_j \sum_k W_{ijk} T_{ijk} \qquad 2.5$$

Where T_{ijk} is the operation time of relay i of zone j for a fault in zone k, and weights W_{ijk} may depend upon the probability of a given fault occurring in each of zones of the protective relays. For the purpose of relay coordination the values for weights is taken to be 1 because the probability of occurrence of fault at any point is equal.

2.3 COORDINATION CRITERIA

The coordination of overcurrent relays in interconnected systems should be done according to certain coordination criterion.

The most important criterion is the time lag in operation between a primary relay and its backup relay. This time lag is known as coordination time interval (*CTI*) and depends upon many factors such as the time of operation of circuit breakers, relay over travel time and factor of safety.

The coordination criterion is written as:

$$T_{nmk} - T_{ijk} \geq CTI \qquad 2.6$$

For the transient configurations that occur when only one relay of a zone has operated, the coordination criterion must still assure a coordinated operation, independently of the tripping sequence, that is:

$$T^1_{nmk} - T^1_{ijk} \geq CTI \qquad 2.7$$

Where the superscript (^{1}) indicates transient configuration quantities.

The coordination criterion is implemented by taking into consideration the time of operation of relay for both close-in and far-bus fault. A fault near a relay is its close-in fault and this will generate its own B/P relay pairs and the associated fault current pairs. Similarly the same fault is a far-bus for the relay which is on the other side of the line and it indeed will generate its own B/P relay pairs and fault current pairs. The value of CTI is taken as 0.2.

2.4 BOUNDS ON RELAY SETTINGS

The range of relay settings is always fixed. The time dial settings and pickup current settings have their own respective upper and lower limits.

$$TDS_{\min} \leq TDS \leq TDS_{\max} \qquad 2.8$$

$$I_{p\min} \leq I_p \leq I_{p\max} \qquad 2.9$$

The allowable range for TDS is taken between 0.01 and 1.10 and for plug setting (PS) between 0.5 and 2.0.

2.5 BOUNDS ON OPERATING TIMES

In addition to the above mentioned coordination criterion and bounds on relay settings; it is also required to have an upper and lower bound on the operation time of primary relays.

$$T_{i\min} \leq T_i \leq T_{i\max} \qquad 2.10$$

Chapter 3

PREPROCESSING OF THE OPTIMAL COORDINATION OF OVERCURRENT RELAYS

3.1 INTRODUCTION

The optimal coordination of overcurrent (OC) relays is a non-linear programming problem and conventionally the operating times of OC relays are minimized subject to coordination criterion described in sections [2.2] to [2.5]. All the selectivity constraints generated for a network are not feasible, so this chapter describes pre-processing of infeasible and redundant constraints.

Both worst and critical case scenario for a power system is considered for future modifications to power systems. Dynamic changes in the network topology produce more constraints [13].

3.1.1 Literature review

A new optimal coordination method has been recently developed by *H.K.Karegar et al.*[13]. In this method all the constraints should be feasible, if some of the constraints conflict, there will be no solution and problem will become infeasible. Therefore, the aim is to first recognize the constraints that make the optimization problem infeasible, and then decrease the complexity of the optimal coordination problem of OC relays by reducing the number of constraints. Of course, the efficient constraints are retrieved and the useless ones are removed.

Before describing the insights of this procedure, a general solution procedure of the coordination problem is presented..

In the coordination program, two types of settings, time dial settings and plug settings are calculated. The current setting for each relay is determined by two parameters: the minimum fault current and the maximum load current . However, the variables of interest in the optimal coordination problem are the *TDS/ TMS* and the plug setting *(PS)*.

To find the *TDS/TMS* and *PS* using optimal programs, the objective functions and constraints are given by:

Minimize:

$$\text{Obj} = \sum_i (W_i f(I_{pi}, I_i) x_i) \tag{3.1}$$

Subject to:

$$t_j - t_i \geq CTI \tag{3.2}$$

$$t_i = f(I_{pi}, I_{fi}) x_i \tag{3.3}$$

$$f(I_{pj}, I_{fj}) x_j - f(I_{pi}, I_{fi}) x_i \geq CTI \tag{3.4}$$

or simply

$$f(PS_j) x_j - f(PS_i) x_i \geq CTI \tag{3.5}$$

$$x_{li} \leq x_i \leq x_{ui} \qquad x_{lj} \leq x_j \leq x_{uj} \tag{3.6}$$

Where each variable has its intended meaning.

3.2 PROBLEM STATEMENT

The optimization process is feasible if the obtained solutions satisfy all the constraints. If any constraint is in conflict to others, then the optimal problem becomes infeasible. It is necessary to recognize these conflicting constraints before performing the optimal coordination process.

For a given fault at point F shown in Fig. 3.1, the original coordination constraint between the primary relay *i* and the backup relay *j*, without considering any configuration change, is given by Eqn [3.4]. If the constraint variables, i.e. *xi* and *xj*, are beyond their maximum and minimum limits, then the solution of problem is impossible.

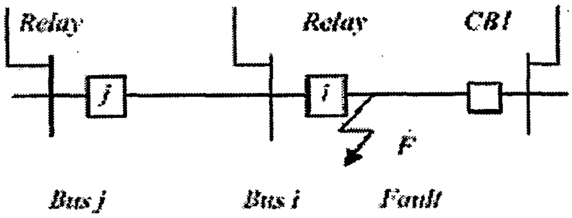

Figure 3.1 A typical primary and backup relays on the part of a power system

In order to explain the procedure, only the optimal calculation of time dial settings is considered, whereas PS's are kept fixed. If the far end circuit breaker (CB), i.e. CB1, is open, then the relays see different network topology and faults current seen by the relays *i* and *j* will be different from the original case. The new constraint, which must be added to the constraints set .

$$f\,(I_{pj}, I_{\_fj})x_j - f\,(I_{pi}, I_{\_fi})x_i \geq CTI \qquad 3.7$$

The normal state of the network is given by Eqns [3.1] to [3.6]. To explain how some constraints make the solution of [3.1 to 3.7] impossible, consider Fig. 3.2. In this figure, the constraint line *A* is described by (3.4) in the plane *xi* and *xj*. The slope and crossing points of the line with *xi* and *xj* axes depend on the coefficients of its variables and the CTI. This line divides the *xi* and *xj* plane into two sections, upper and lower. The upper section contains any possible optimal settings of a P/B pair satisfying Eqn [3.4], while expression [3.6] defines the possible solution area in the *xi* and *xj* plane. This square area is bounded by the maximum and minimum values of the variables *xi* and *xj*, shown in Fig.3.2. As can be seen from this figure, although all points on the upper section of the line satisfy the equation, only those that lie within the maximum and minimum of *TDS/TMS* are chosen. This is the common area between the upper section and PSA. This area is defined as the feasible solution area (FSA).

Optimization becomes impossible when any of the constraint lines are above the PSA. In the traditional optimization coordination process there is no way to detect this and the process does not simply converge. However, by a pre-analysis method non-valid constraints can be detected and excluded. Then the problem can be solved.

The full analysis on how to detect useless constraints and the method to have a feasible solution are given in the next section.

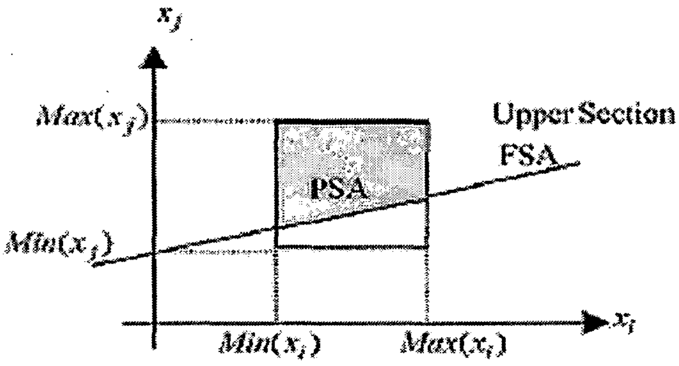

Figure 3.2 PSA and FSA

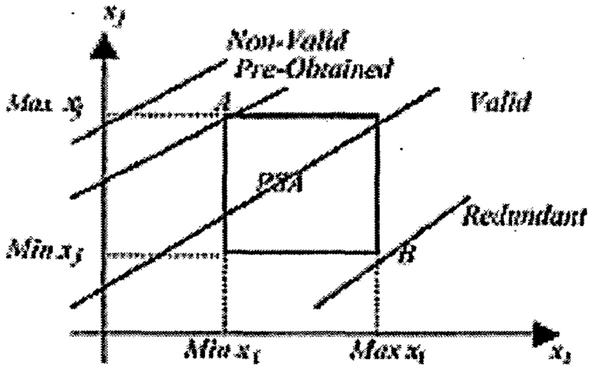

Figure 3.3 Four categories of constraint lines

3.3 THEORETICAL APPROACH

3.3.1 Constraints recognition

This section is based on the intersection of constraints lines of the P/B pairs with the PSA. In this phase, the validity of each constraint is examined.

As mentioned in the previous section, the optimal solution for a P/B relays pair exists if the upper section and the PSA have a common area. Based on this, constraints lines shown in Fig. 3.3 are classified into four categories as follows:

- Non-valid
- Pre-obtained
- Redundant
- Valid.

If a constraint line is sited above the PSA and does not have any common area with the PSA, then it is classified as a non-valid constraint. If this constraint is not excluded from the constraints set, then the optimal coordination program will be disturbed, i.e. the optimization will become impossible.

The criterion to designate a constraint as a non-valid one is stated by Eqn [3.8] because if the right hand side of a constraint for the point *A* is smaller than the CTI, then it means that there is no intersection between that constraint and the PSA. In this expression the characteristics of point *A* are Max(x_j) and Min(x_i).

$$f_j(I_{pj}, I_{fj})\ Max(x_j) - fi(I_{pi}, I_{fi})\ Min(x_i) < CTI \qquad 3.8$$

If a constraint line crosses the PSA at only one point, i.e. the point *A*, then the only optimal solutions for the variable x_i and x_j are Min(x_i) and Max(x_j). This type of constraints is known as the pre-obtained, which can be recognized by .

$$fj(I_{pj}, I_{fj})\ Max(x_j) - fi(I_{pi}, I_{fi})\ Min(x_i) = CTI \qquad 3.9$$

The redundant constraint is a constraint in which its line does not intersect with the PSA and is sited below it. In this case, any arbitrary point within the PSA is a possible solution. Therefore, this constraint can be excluded from the constraints set because it does not inhibit any point within PSA.

Eqn. [3.10] describes how to find a redundant constraint. The point *B* is specified by (Max(x_i), Min(x_j)).

$$f_j(I_{pj}, I_{fj})\ Min(x_j) - fi(I_{pi}, I_{fi})\ Max(x_i) \geq CTI \qquad 3.10$$

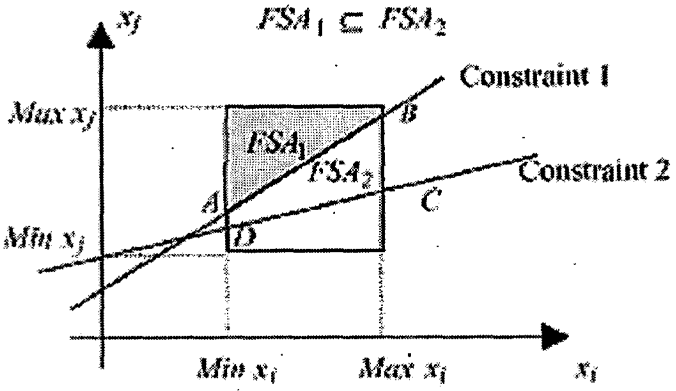

Figure 3.4 Comparing two valid constraints

Finally, the valid constraint is a constraint whose line passes through the PSA. The upper-bounded area between the valid line and the PSA is the FSA where the optimal solutions of x_i and x_j exist. Therefore, the valid constraints are kept in the constraint set while others are removed. As a consequence, the constraint set includes fewer constraints and the solution area is reduced.

3.4 RESULTS AND CONCLUSION

The performance of the proposed method was evaluated on a 6-bus test power system [Fig A.1] and IEEE 14-bus test power system [Fig A.2].

In the procedure described above, only *TDS*'s are evaluated (*PS* is considered as constant i.e., problem is considered as linear programming problem). While actually solving the problem, it is considered as non-linear and the optimization of *PS* is also taken into consideration. Therefore, whenever minimal of *TDS* is considered, a corresponding maximal of *PS* is taken and vice versa.

For 6-bus test power system, it is observed that out of all the generated 60 coordination constraints, only 40 constraints were found to be qualifying to be considered in the coordination process. In the case of IEEE 14-bus test system, out of 184, 141 were qualified for coordination process.

Thus after pre-processing only the valid constraints remain. It becomes possible to obtain the feasible solution decreasing the memory requirement and run-time of the program.

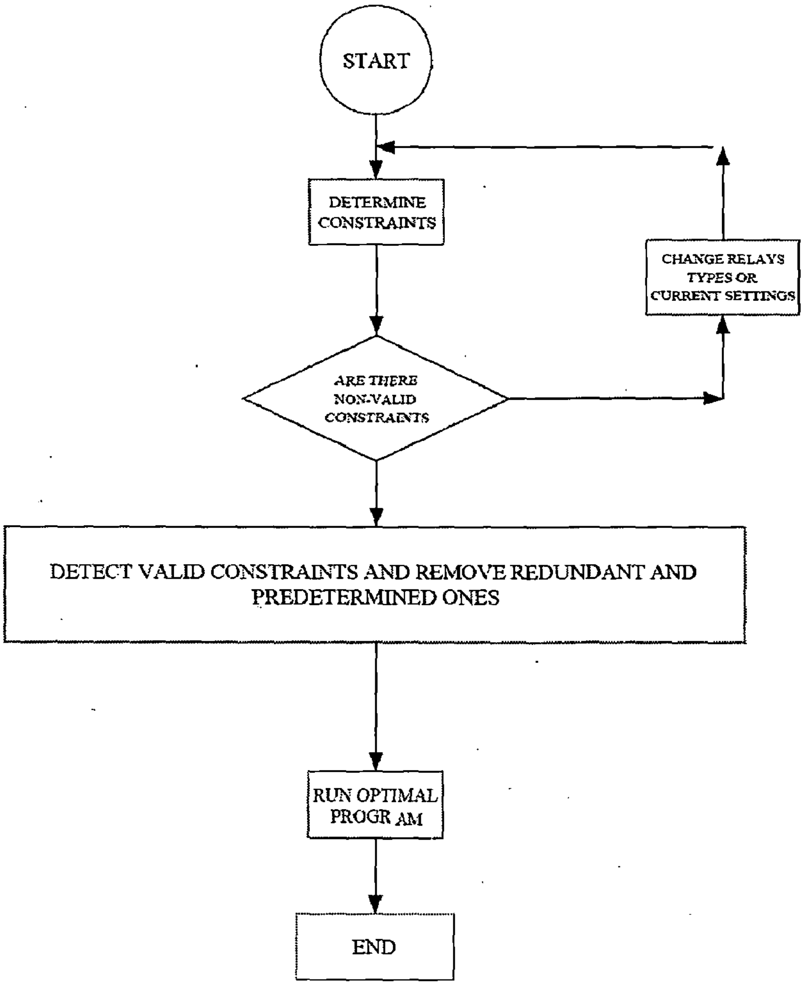

Figure 3.5 Flow chart of the optimal program with pre-processing

Chapter 4

ALGORITHMS FOR OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAY COORDINATION

4.1 GENERAL METHODOLOGY ADOPTED

The problem of overall relay coordination is divided into two sub problems, viz. the optimal selection of *TDS* and optimal selection of I_p. The division of the problem facilitates a natural partition between *TDS* and I_p. The solution of the coordination problem of an interconnected power system involves minimizing the objective function given in (2.5) and subject to the constraints given in Equations (2.6) to (2.10). The overall problem is solved by an iterative procedure in which the time dial settings are computed for a given set of pickup currents, and vice versa, until convergence is achieved. The procedure (which is based upon the Gauss-Seidal method) adopted is:

1. An initial value of I_p is selected for all relays.
2. For the optimal selection of *TMS,*
   Minimize Eqn [2.5]
   Subject to the constraints given in Eqns. [2.6], [2.7], [2.8] and [2.10].
3. For this value of *TMS,* to get I_p,
   Minimize Eqn [2.5]
   Subject to the constraints given in Eqs. [2.9] and [2.10].
4. Go to step 2 with new values of I_p settings, until convergence is achieved

4.1.1 Optimal coordination of TDS

The optimal coordination problem of directional overcurrent relays is a nonlinear optimization problem (for fixed I_p) due to the fact that time dial settings are related to the operation times T_{ijk} in a nonlinear fashion. Therefore whenever it is possible to relate these variables using a linear expression the problem of finding *TDS* reduces to a linear programming problem. This is the case when relay characteristics are of the type indicated by Equation [2.3], and the pickup currents are assumed to be known. In this case the equations of the relays can be rewritten in the following form which relates *TDS* and T_{ijk} linearly:

$$T_{ijk} = K_{ijk} TDS_{ij}$$

Where:

$$K_{ijk} = \frac{k_1}{\left[\left(\frac{I_{ijk}}{I_{p_{ij}}} \right)^{k_2} + k_3 \right]}$$

Therefore the problem is simplified to a linear programming problem with Eqn [2.5] subjected to constraints of Eqns [2.6] to [2.8]. Simplex method has been used to find the optimal solution for this part of the problem.

4.1.2 Optimal coordination of I_p

For a given *TDS*, the relay characteristics from Eqn [2.3] are written as:

$$T_{ijk} = \frac{k_1 * TDS * (I_p)^{k_2}}{(I)^{k_2} + (I_p)^{k_2} . k_3}$$

The performance function in this case is non-linear and is in terms of variable I_p. This performance function is to be minimized subject to the constraints give by Eqns [2.6], [2.7], [2.9] and [2.10].

Rosenbrock-hillclimb algorithm, Box (complex) algorithm and Interior primal dual algorithm etc have been used by researchers to solve thus formed non-linear problem.

In the present work, the nonlinear optimization problem is solved by using exterior penalty approach and thereby arriving at a solution by steepest descent method. (The algorithms related to steepest descent and exterior penalty methods is presented in appendix A).

Before going into actual algorithm, it is necessary to carry out load flow analysis and fault analysis. A three phase fault is simulated at each end of a transmission line and fault currents are computed in order to perform coordination analysis.

4.1.3 Results obtained by Gauss-Seidal approach described in section 4.1

Table 4.1 For 6-bus test power system [Fig A.1]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.7516	1.5000
2	0.4994	1.4564
3	0.4998	1.4896
4	0.5036	1.5164
5	0.5234	1.8347
6	0.5148	1.2358
7	0.5006	1.2980
8	0.5000	1.5000
9	0.5000	1.5000
10	0.4800	1.5000
11	0.4967	1.5016
12	0.5000	1.6661
13	0.5108	1.5000
14	0.5000	1.4822
15	0.5000	1.4964
16	0.4884	1.5000

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 35.8697seconds

4.2 RELAY COORDINATION AS A NON-LINEAR PROGRAMMING PROBLEM

In this case, unlike Gauss-Seidal approach, the problem is solved by considering the entire problem at a time simultaneously optimizing both *TDS*'s and *PS*'s. The results are presented below:

4.2.1 Results obtained for 6-bus and IEEE 14-bus test systems

Table 4.2 For 6-bus test power system [Fig A.1]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.3736	1.3017
2	1.1411	0.5010
3	0.5000	0.8362
4	0.5000	1.5000
5	0.5000	1.5022
6	0.5091	1.4533
7	0.1756	1.6434
8	0.5000	1.4347
9	0.5000	1.4759
10	0.3478	1.5797
11	0.5000	1.4733
12	0.5811	0.9906
13	0.3794	1.2430
14	0.3777	1.5000
15	0.5000	1.5000
16	0.5000	1.4876

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 27.1943 seconds

With the relay settings obtained, it is found that out of 40 qualified coordination constraints considered for coordination, 34 constraints satisfied. In the remaining 6 constraints, it is observed that the corresponding backup relays operate before the primary relays.

Table 4.3 For IEEE 14-Bus test power system [Fig A.2]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.5000	1.5000
2	0.0000	0.0000
3	0.5000	1.4756
4	0.4986	1.5026
5	0.0000	0.0000
6	0.5012	1.5000
7	0.5004	1.4896
8	0.5000	1.2767
9	0.5106	1.5000
10	0.5055	1.8367
11	0.5000	1.5000
12	0.4976	1.5000
13	0.5012	1.4585
14	0.4998	1.4996
15	0.4094	1.0987
16	0.5000	1.1586
17	0.5000	1.5000
18	0.5000	1.5000
19	0.5000	1.5036
20	0.5006	1.4864

21	0.6940	1.7477
22	0.5856	1.5010
23	0.4867	1.5003
24	0.5000	1.5000
25	0.0618	1.4639
26	0.5000	1.5000
27	0.1205	0.8322
28	0.5000	1.5000
29	0.5000	1.5679
30	0.5141	1.6022
31	0.5000	1.5000
32	0.4986	1.9612
33	0.5011	1.3197
34	0.5000	1.5000
35	0.5000	1.5000
36	0.4935	1.5045
37	0.5075	1.5084
38	0.5000	1.4997
39	0.5000	1.3639
40	0.5012	1.5000
41	0.5102	1.4998
42	0.5000	1.5000

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 167.3088 seconds

With the relay settings obtained, it is found that out of 141 qualifying coordination constraints considered for coordination, 121 constraints are satisfied. In the remaining 20 constraints, it is observed that the backup relays operate before the primary relays.

The results that are presented above were obtained by considering the objective function as the minimization of sum of primary operating times of all the relays for both close-in and far-end faults. In the next section, the objective function is modified, which helps in satisfying more constraints thereby increasing the reliability of the system.

4.3 A NEW OBJECTIVE FUNCTION

The main objective in relay coordination problem is minimization of the operating times of relays. In all the cases above, for which the coordination problem is solved, importance is given to the speed of operation of relays and by doing so, in certain situations, selectivity and reliability of the protection system is sacrificed.

H.O Gupta et al[17] in their forthcoming paper has suggested that, instead of taking the objective function as minimization of operating times of relays, if it is taken as minimization of sum of constraint violations, better results are expected to be achieved. The results that are presented below are obtained by considering the same.

The original objective function was

$$\min \sum_i \sum_j \sum_k W_{ijk} T_{ijk}$$

Where W_{ijk} and T_{ijk} have their respective meanings.

Now the objective function will be

$$\mathbf{min} \sum_i \sum_j \sum_k (CTI - (T_{nmk} - T_{ijk}))$$

Only when there is a violation in any coordination constraint.

4.3.1 Results obtained for 6-bus and IEEE 14-bus test systems

Table 4.4 For 6-bus test power system [Fig A.1]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.3620	1.4698
2	0.4237	1.4866
3	0.4060	1.4825
4	0.3758	1.4799
5	0.5000	1.5000
6	0.5718	1.5083
7	0.5692	1.5119
8	0.4660	1.4973
9	0.5440	1.5070
10	0.5911	1.5213
11	0.5000	1.5000
12	0.5000	1.5000
13	0.4843	1.5016
14	0.5000	1.5000
15	0.6750	1.5207
16	0.5376	1.5034

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 35.4345 seconds.

Table 4.5 For IEEE 14-Bus test power system [Fig A.2]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.5000	1.5000
2	0.0000	0.0000
3	0.4996	1.4896
4	0.5012	1.5000
5	0.0000	0.0000
6	0.3981	1.4940
7	0.5000	1.5000
8	0.5000	1.5000
9	0.5012	1.5000
10	0.5695	1.5134
11	0.4998	1.8525
12	0.5000	1.5000
13	0.4075	1.2501
14	0.4916	1.4998
15	0.5000	1.5000
16	0.3800	1.4292
17	0.5000	1.5000
18	0.5000	1.5000
19	0.5750	1.3674
20	0.5000	1.5000
21	1.0952	1.5898
22	0.7156	1.5401
23	0.6631	1.5226
24	0.4855	1.4673

25	0.0409	1.4546
26	0.5000	1.5000
27	0.4370	1.1000
28	0.2940	1.7407
29	0.8332	1.5561
30	0.7418	1.5295
31	0.8072	1.4913
32	0.7473	1.5356
33	1.0349	1.5783
34	0.5000	1.7296
35	0.8767	1.6382
36	0.5000	1.5000
37	0.5000	1.5000
38	0.5000	1.0033
39	0.7082	1.6355
40	0.9098	1.4816
41	0.5000	1.5000
42	0.3817	1.9762

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 179.4784 seconds.

It is observed that out of total 141 qualifying constraints considered for coordination after excluding nearly 43 constraints by preprocessing method described in the previous chapter, 131 constraints are satisfied. It is observed that there is a significant improvement in the solution as far as selectivity and reliability are concerned. Therefore it can be concluded that by modification of objective function to sum of minimization of constraint violations, quality of coordination is improved.

Table 4.6 Performance evaluation of the relays for 6-bus test power system

Fault near Relay	Type of fault	Primary relay		Backup relay		Remarks
		Relay	Operating time(seconds)	Relay	Operating time(seconds)	
1	Close-in	1	1.3858	10	2.2011	All operate
	Far-bus	13	1.5308	3	2.3105	
2	Close-in	2	1.2835	13	1.5322	Relay pair 4-13 under any circumstances satisfy coordination criterion
	Far-bus	10	2.1991	4 9	------ 3.7398	
3	Close-in	3	0.9786	8 11 15	------ 1.6358 1.3063	Relay 8 does not operate due to directional restraint. Relay 1 does not operate because Ifault<Ip
	Far-bus	14	1.5510	1	------	
4	Close-in	4	0.7276	8 14 15	------ 1.5549 1.3069	Relay 8 and 9 does not operate due to directional restraint. Relay 2 does not operate because Ifault<Ip
	Far-bus	11	1.6040	2 9	------ ------	
5	Close-in	5	0.8067	8 11 14	------ 1.6355 1.5524	Relay 8 does not operate due to directional

	Far-bus	15	1.3053	7	1.5028	restraint
6	Close-in	6	0.8007	11 14 15	1.6360 1.5528 1.3067	Relay 8 and 16 does not operate due to directional restraint
	Far-bus	8	------	12 16	2.2878 ------	
7	Close-in	7	1.0304	6 12	1.2281 1.3114	Relay pair 5-16 does not satisfy coordination criteria
	Far-bus	16	0.9200	5	------	
8	Close-in	8	0.7206	12 16	1.3116 0.9205	Relay 15 does not operate due to directional restraint
	Far-bus	6	1.2272	11 14 15	3.7606 2.5317 ------	
9	Close-in	9	0.9387	6 16	1.2281 0.9205	Relay 4 does not operate due to directional restraint. Relay 2 does not operate because Ifault<Ip
	Far-bus	12	1.3107	2 4	------ ------	
10	Close-in	10	1.4244	4 9	1.7685 1.6244	All operate
	Far-bus	2	1.9380	13	2.3647	
11	Close-in	11	0.8994	2 9	1.9475 1.6294	Relay 8 and 14 does not operate due to directional restraint
	Far-bus	4	1.3130	8 14	------- -------	

				15	1.8575	
12	Close-in	12	0.7371	2 4	1.9417 1.3401	Relay 16 does not operate due to directional restraint
	Far-bus	9	1.6223	6 16	3.7432 ------	
13	Close-in	13	1.2004	3	1.3988	All operate
	Far-bus	1	1.7351	10	2.7377	
14	Close-in	14	1.0683	1	1.7387	Relay 8 and 11 does not operate due to directional restraint
	Far-bus	3	1.3967	8 11 15	------ ------ 1.5947	
15	Close-in	15	------	7	------	Relay 15 and 7 does not operate due to directional restraint
	Far-bus	5	1.0240	8 11 14	1.3668 2.2847 1.9785	
16	Close-in	16	0.7550	5	2.0969	Relay 7 and 6 does not operate due to directional restraint
	Far-bus	7	------	6 12	------ 1.5137	

It is observed that out of total 40 qualifying constraints considered for coordination after relaxing nearly 20 constraints by preprocessing method described in the previous chapter, 38 constraints are satisfied.

Therefore it is seen that by taking the objective function to be the sum of minimization of constraint violations, the protection system becomes more selective and more reliable as compared to conventional objective function though the speed of the protection slightly decreases.

4.4 MODIFIED COORDINATION PROBLEM

The coordination problem is modified by removing those constraints which make the system infeasible. Most of the constraints are removed by preprocessing method. The constraints which are not satisfied even after the consideration of new objective function (presented in section [4.3]) are also eliminated. Only those constraints which make the optimization problem feasible are taken into consideration.

By doing so, it is found that, there is betterment in the original objective function value.

4.4.1 Results obtained for 6-bus and IEEE 14-bus test systems

Table 4.7 For 6-bus test power system [Fig A.1]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.3345	1.4637
2	0.2748	1.4590
3	0.4711	1.4870
4	0.3901	1.4823
5	0.5000	1.5000
6	0.5428	1.5048
7	0.5856	1.5129
8	0.4732	1.4979
9	0.5458	1.5072
10	0.5936	1.5227
11	0.5000	1.5000
12	0.5000	1.5000
13	0.5708	1.5149
14	0.5000	1.5000
15	0.7390	1.5283
16	0.5297	1.5027

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 35.0603 seconds

Table 4.8 For IEEE 14-Bus test power system [Fig A.2]

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.5000	1.5000
2	0.0000	0.0000
3	0.4996	1.4896
4	0.5012	1.5006
5	0.0000	0.0000
6	0.3981	1.4940
7	0.5000	1.5007
8	0.5000	1.5000
9	0.5012	1.4998
10	0.5695	1.5134
11	0.4998	1.8525
12	0.5000	1.5000
13	0.4075	1.2501
14	0.4916	1.4998
15	0.5004	1.5000
16	0.3800	1.4292
17	0.4998	1.5000
18	0.5000	1.5000
19	0.5750	1.3674
20	0.5000	1.5000
21	0.4987	1.5929
22	0.7156	1.5401
23	0.6655	1.5230
24	0.5104	1.4713
25	0.0409	1.4546

26	0.5000	1.5000
27	0.4370	1.1000
28	0.2940	1.7407
29	0.8191	1.5539
30	0.7454	1.5300
31	0.8072	1.4913
32	0.7544	1.5370
33	1.0198	1.5754
34	0.4857	1.7275
35	0.8751	1.6380
36	0.5004	1.5000
37	0.4908	1.5000
38	0.5000	1.0033
39	0.7082	1.6355
40	0.9098	1.4816
41	0.5000	1.5000
42	0.3817	1.9762

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 177.2006 seconds.

Chapter 5

DECOMPOSITION METHOD FOR DIRECTIONAL OVERCURRENT RELAY COORDINATION

In the recent years, with the increase in demand, the size and complexity of power system has grown tremendously. It is difficult and time consuming to analyze such networks as a whole, particularly for coordinating relays of the power network. Hence, there is a need to develop a decomposition method which would be helpful in determining the coordinated relay settings. In the decomposition method, the power network is divided into a number of areas. The need for subdivision into areas arises due to the complexity and computational difficulty associated with a single large power network, geographical disposition of generating sources, heavy load centers, interconnections, different ownerships, political boundaries and overall considerations of reliability.

If the network area is very large, then the area may further be divided into sub-areas. The subdivision should be made such that each sub-area is as self-sufficient as possible, in terms of both; generating capacity and interconnection support. This criterion would be a sound principle for control and reliability. Thus, it is preferred to decompose the power network at structural level.

In this chapter, a network decomposition method is presented which determines the coordinated relay settings of power network area-wise or region-wise. The method utilizes optimization techniques to solve the coordination problem of the directional overcurrent relays.

5.1 LITERATURE REVIEW

The idea of network decomposition or network tearing is not new. It has been used for conducting the load flow studies on large power systems for many years.

Kron [25] was pioneer to develop the idea of partitioning the network into sub-networks. Other researchers like *Happ*[23], *Andretich et al.*[20],, *Sasson*[27], *Happ et al*[22], *Roy*[26], *Kasturi et al* [24], *Alvardo et al* [19] and *Agnihotri et al*[18] also developed methods to solve the load flow problems of large power networks. In all these methods, a power network is decomposed into several sub-networks and the sub-networks are solved in turn, one by one. These methods are efficient as far as the speed of execution and memory requirements are concerned.

This chapter presents the developed network decomposition optimal coordination method. During this work, the large power network is decomposed into number of sub-networks called blocks by identifying boundary buses, branches and the relays. The blocks are analyzed sequentially and the boundary data table is updated during the solution process. The method reported is distinctly superior to the full system optimal coordination method from the point of view of speed and memory requirements. The results are discussed for IEEE 14-bus system.

5.2 DECOMPOSITION METHOD FOR COORDINATION

Assume that a large power network N^0 is decomposed into sub-networks N^1 and N^2 as shown in Fig.[5.1]. These sub-networks are called blocks. The blocks are connected with each other with the help of boundary lines. There may one or more than one boundary lines between different blocks. In case of Fig.[5.1] , there are two boundary lines between blocks N^1 and N^2. These boundary lines are connected to boundary buses of each block. Each boundary line has two boundary relays installed at its two ends. These boundary relays are classified as the external boundary relays and the internal boundary relays, depending upon which block is currently analyzed. Consider block N^1 of Fig.[5.1], the internal boundary relays are R_1, R_4. The external boundary relays are R_2, R_3 (which are a part of internal boundary relays of block N^2). Similarly R_2 and R_3 are the internal boundary relays of block N^2 and the relays which are installed on the other end of boundary lines connected to this block are the external boundary relays. Therefore a boundary relay belongs to its own block as an internal boundary relay and as external boundary relay for the adjacent blocks.

Now, if a fault occurs near bus N^1_{m1} at location (A) , the directional overcurrent relay R_1 will act as primary relay for the close-in fault and the appropriate relays of block N^1 will act as backup relays. The same fault is a far-bus fault for the relay R_2 which falls under the jurisdiction of block N^2. Thus, the relay R_2 will operate as a primary relay to a fault in block N^1 along with its appropriate backup relays which are a part of block N^2. Moreover, the relay R_1 acts as a backup relay for a relay which falls under block N^2 and similarly R_2 acts as a backup relay to other primary relays of block N^1.

For the sake of decomposing the network into blocks and making them disassociated or independent from each other for individual analysis along with their boundary relays, the close-in faults and the far-bus faults are not considered for external boundary relays. As an example, for block N^1 fault at location A is a far-bus fault for relay R_2 and fault at location B is close-in fault for the same relay. These faults are not considered for relay R_2 as far as the analysis of block N^1 is concerned. This step limits the role of external boundary relays to that of backup relays only. Similar is the case when block N^2 is considered. For relay R_1, no close-in and far-bus faults are considered. This step helps in delinking the various blocks and making them independent for individual analysis. To summarize, the external boundary relays appear only as the backup relays to the primary relays of the block under consideration. The boundary relays belong to their own blocks as well as to other blocks simultaneously. This special feature of interdependence is utilized in the proposed decomposition method which greatly enhances the efficiency of the coordination solution algorithm. This feature of interdependence is exploited in the manner as explained below:

Each directional overcurrent relay has three settings to be determined: I_s, I_p and *TMS*. In order to ensure the selective operation of the relays, proper coordinated values of *TMS* and I_p have to be determined for each block, an objective function or a performance function is minimized subject to coordination criterion and the limits on the relay settings. The objective function chosen must reflect the desired operation of the relays. The coordination problem of each block is formulated as a parameter optimization problem.

$$\text{Minimize } F = \sum_{i=1}^{N_B} T_{p_i}$$

Subject to

$$T_{b_b} - T_{p_c} \geq CTI$$

$$T_{b_f} - T_{p_f} \geq CTI$$

$$TMS_i^{\min} \leq TMS_i \leq TMS_i^{\max}$$

$$I_{p_i}^{\min} \leq I_{p_i} \leq I_{p_i}^{\max}$$

Where $i = 1, 2 \ldots \mathrm{NB}$

$$TMS_J = TMS_{IBR}$$

$$PS_J = PS_{IBR}$$

Where, F is the summation of the primary operating times (Tp) of all the relays of a block, including that of the boundary relays. Two types of the primary relays are considered: one type which responds to close-in faults and the other which responds to far-bus faults. TMS_J are the time multiplier settings of the internal boundary relays (IBR) of each block which are kept fixed during the analysis of the block. Same is the case with plug multiplier settings.

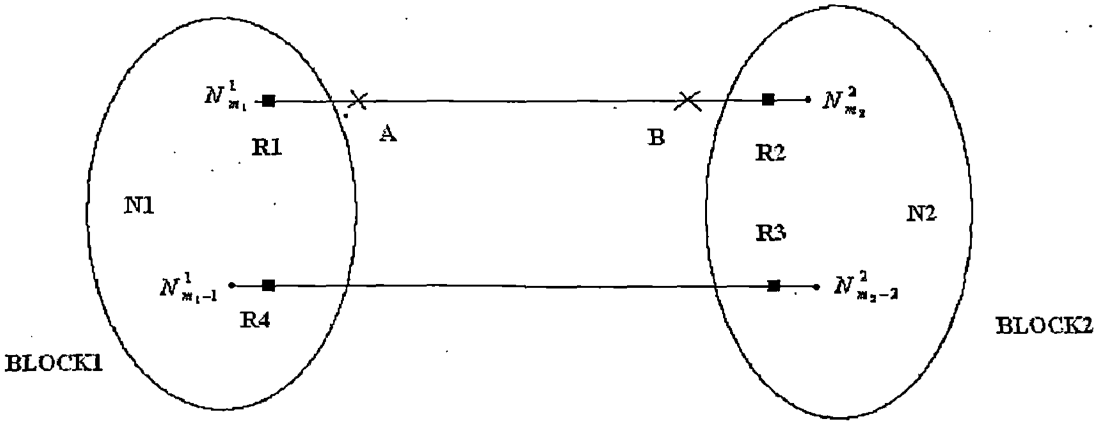

Figure 5.1. Interconnection of blocks

Consider Fig.[5.1] to begin with, the coordination problem of block N^1 is solved. The *TMS* and *PS* for the internal boundary relays are not kept fixed at this stage because there are no previous *TMS* and *PS* results available. The *TMS* and *PS* of the external boundary relays of block N^1 are preserved. These become the *TMS* and *PS* of the internal boundary relays of block N^2 (only those relays which are connected to block N^1). Now block N^2 is analyzed, keeping the *TMS* and *PS* of its internal boundary relays fixed. The *TMS* and *PS* of the external boundary relays of block N^2 are preserved. Then again block N^1 is analyzed and so on. Thus the analysis of the blocks is continued till the convergence is achieved. The convergence criterion selected depends upon the *TMS* and *PS* of the boundary relays. After each iteration, the *TMS* and *PS* of the boundary relays are checked. If there is no change in *TMS* and *PS* values, the algorithm stops, otherwise another iteration is taken.

5.3 ALGORITHM

The decomposition method described is used to decompose the power network into blocks. All the blocks are solved sequentially and the solutions are coordinated simultaneously to get the overall optimal settings of the directional overcurrent relays.

The main steps of the algorithm are:

1. The load flow analysis is performed for the whole system under consideration to determine the bus voltages and line currents.
2. Z-Bus matrix is built for the complete system. This matrix is put to use to perform the fault analysis of the power system.
3. The next step is to decompose the power network into blocks. Blocks are formed in any convenient manner one may like. Normally blocks are formed with minimum number of boundary relays between them. At this stage data is read about the relays of each block and the external and internal boundary relays of each block.
4. ITER <—— 1
5. I <—— 1
6. A fault is simulated at every relay location of block I. The B/P relay pairs and the associated fault currents are determined and stored.
7. The coordination problem is solved ,by using the methods already presented in the previous chapters for block I. For the first iteration, if block I is analyzed, TMS and PS values are not kept fixed for the internal boundary relays, but for subsequent iterations these are kept fixed.
8. The TMS and PS values of all the boundary relays are updated for block I.

9. if it is the first iteration and all the blocks have not considered, set I=I+1 and go to step 6 ; otherwise go to step 11.
10. Set ITER=ITER+1
11. If the convergence of TMS and PS of the boundary relays is not achieved ,set I=I-1 and go to step 6; otherwise stop.

5.4 APPLICATION TO IEEE 14-BUS POWER SYSTEM AND RESULTS

While formulating the coordination problem, the objective function is taken as the minimization of coordination constraint violations instead of operating times of the relays. As already mentioned in the previous chapter that by taking so, a fast convergence of solution is achieved and moreover there is an improvement in the number of feasible constraints.

The IEEE 14-bus power system is shown in Fig.[5.3]. Line XX-X divides the network into two blocks, block1 and block2. Relays numbered 17, 18 and 19 are the internal boundary relays of block1 and the external boundary relays of block2. Similarly relays 20, 28 and 42 are internal boundary relays for block2 and external boundary relays for block1. First, block1 is solved. No relay has fixed value of *TMS* and *PS* at this stage. The *TMS* and *PS* values for relays 20, 28 and 42 are stored. After block1 is solved, the algorithm solves the coordination problem of block2, keeping the TMS and PS of relays 20, 28 and 42 fixed. The *TMS* and *PS* of relays 17, 18 and 19 are preserved. Then again block1 is solved, but this time the *TMS* and *PS* values of relays 17, 18 and 19 are kept fixed and *TMS* and *PS* values of 20, 28 and 42 are preserved. Block 2 is again solved keeping the *TMS* and *PS* values of relays 20, 28 and 42 fixed. After each iteration, the criterion for convergence is checked and it is observed at the end of 10 iterations, it is achieved.

During each iteration, the coordination constraints comprising the boundary relays are observed and it is found that all constraints are well satisfied. By doing so, proper coordination of relays is achieved.

Table 5.1 For IEEE 14-Bus test power system

Relay	Time multiplier setting (TMS) (0.05-1.10)	Plug setting (PS) (0.5-2.0)
1	0.5000	1.5000
2	0.0000	0.0000
3	0.5000	1.5000
4	0.5000	1.5000
5	0.0000	0.0000
6	0.4998	1.5000
7	0.5025	1.5000
8	0.5000	1.5000
9	0.3958	1.0111
10	0.5417	1.5081
11	0.8936	1.5710
12	0.5000	1.5000
13	0.4585	1.4920
14	0.5000	1.5000

15	0.5000	1.5000
16	0.4280	1.4575
17	0.6238	0.5076
18	0.5000	1.5000
19	0.5000	1.5000
20	0.5721	1.5425
21	1.0033	1.5758
22	0.5014	1.5002
23	0.7211	1.5335
24	0.5851	1.5151
25	0.5000	1.5000
26	0.5000	1.5000
27	0.4964	1.4978
28	0.5000	1.5000
29	0.9395	1.5898
30	0.9913	1.5761
31	0.7049	1.7141
32	0.9729	1.7646
33	0.9269	1.5752

34	1.0431	1.9563
35	0.9596	1.6580
36	0.5000	1.5000
37	0.5000	1.5000
38	0.5000	1.5000
39	0.6789	1.5322
40	0.5000	1.7803
41	0.4740	1.4983
42	0.6061	1.5441

Objective function = sum of operating times of all the relays for both close-in and far-bus faults= 158.4784 seconds

It is observed that out of 141 coordination constraints, at the end of 10th iteration, nearly 131 constraints are satisfied. The sum of primary operating times of all the relays for both close in and far bus faults is the original objective function. The value for this function is improved to 158.4784 as compared to previous values. It is concluded from the results that by decomposition approach, the results obtained are better than the one obtained by considering the system as a whole. It is because by decomposition approach, the feasible solution area is also divided besides the network and the possibility to achieve a better solution for small system is more. Moreover the algorithm presented to solve the non-linear programming problem is more effective when the system is small.

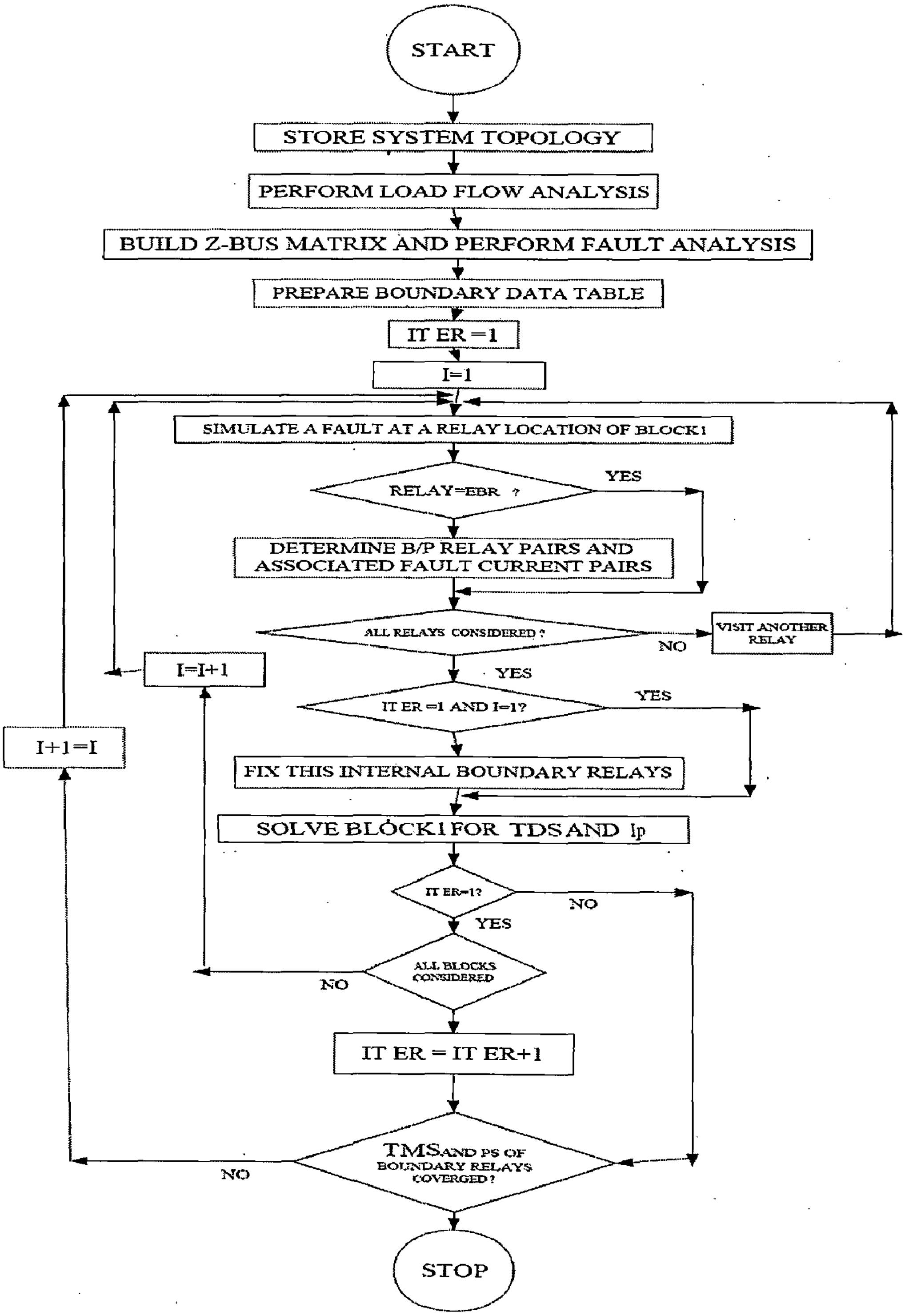

Figure 5.2 Flow chart for optimal decomposition coordination algorithm

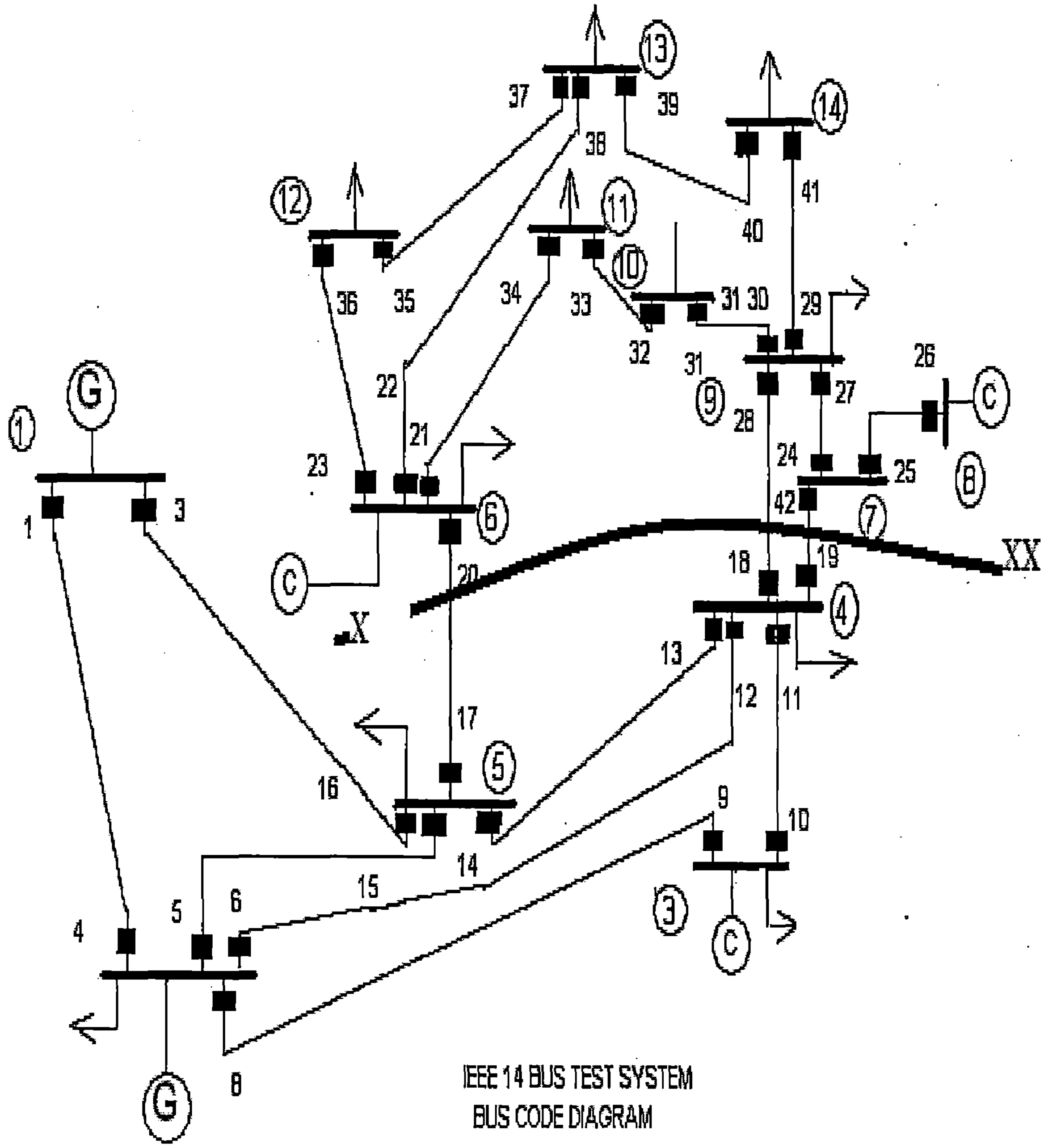

Figure 5.3 Decomposition of IEEE 14-bus test power system along X=XX

Chapter 6

CONCLUSIONS

The parameter optimization method has been studied in detail for solving the relay coordination problem. This realization has eliminated the use of complex topological analysis programs and has simplified the coordination philosophy to a great deal.

While formulating the coordination problem, the main objective was to minimize the operating times of the relays under the requirements of sensitivity, Selectivity, Reliability and Speed. The algorithm developed during this dissertation work, eliminates the infeasible constraints by a pre-processing method. Steepest Descent (Gradient) method is adopted with exterior penalty approach to solve the coordination problem. Exterior penalty method is considered because of the ease with which initial value for algorithm is selected.

The new objective function which tries to improve the reliability of protection system is used. The new objective function is the sum of minimization of constraint violations. It is observed that by doing so, there is a significant improvement in the solution in.terms of reliability and selectivity.

The decomposition methodology has been used, which decomposes the large size power network into a number of blocks. A block or group of blocks may represent a zone/ area and constraints associated with a particular area can easily be included. The blocks with boundary relays are solved in a sequence iteratively for the coordinated relay settings using optimization methods. It has been observed that a considerable saving in memory and CPU time is achieved by doing so. Whenever the system is decomposed into blocks and is solved by the optimization method, the possibility to obtain a better solution is increased.

The system is decomposed into blocks, thereby decomposing the feasible solution area also, as the large feasible solution area is divided accordingly.

Whenever the feasible area is small, there is a possibility to attain a desired solution quickly by the developed gradient algorithm. By decomposition method, the constraints comprising boundary relays may degrade the solution to some extent. Therefore to ensure a better coordination, boundary relays should be minimum and some better criterion in order to changeover from one block to another during iterative procedure is desired. In the work presented in this report, the criterion, to changeover from one block to another is the settings of the internal boundary relays are kept fixed and that of external boundary relays are retained while considering a block.

Relay coordination is an art and has no limited scope. In future, pre-processing and decomposition methods used in this work can be extended to cover the contingencies, sympathy trips etc. along with other aspects of ccordination.

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APPENDIX - A

6-bus system: Bus data

BUS NO.	BUS TYPE	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPTANCE (P.U)
		MAGNITUDE (P.U)	ANGLE (RADIANS)	ACTIVE (MW)	REACTIVE (MVAR)	ACTIVE (MW)	REACTIVE (MVAR)	
1	0	0.9795	-0.6602	0.000	0.000	2.400	0.000	0.000
2	0	0.9941	-0.2976	0.000	0.000	2.400	0.000	0.000
3	0	0.9355	-0.3036	0.000	0.000	1.600	0.400	0.000
4	2	1.0200	-0.5566	1.900	0.270	0.500	0.100	0.000
5	2	1.0400	-0.4740	3.000	0.631	0.500	0.200	0.000
6	3	1.0400	0.0000	2.760	0.840	0.000	0.000	0.000

6-bus system: Line data

LINE NO	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U)
				RESISTANCE (P.U)	REACTANCE (P.U)	
1	1	1	4	0.0500	0.2000	0.0
2	1	1	5	0.0250	0.1000	0.0
3	1	2	3	0.1000	0.4000	0.0
4	1	2	4	0.1000	0.4000	0.0
5	1	2	5	0.0500	0.2000	0.0
6	1	2	6	0.1875	0.0750	0.0
7	1	3	4	0.1500	0.6000	0.0
8	1	3	6	0.0375	0.1500	0.0

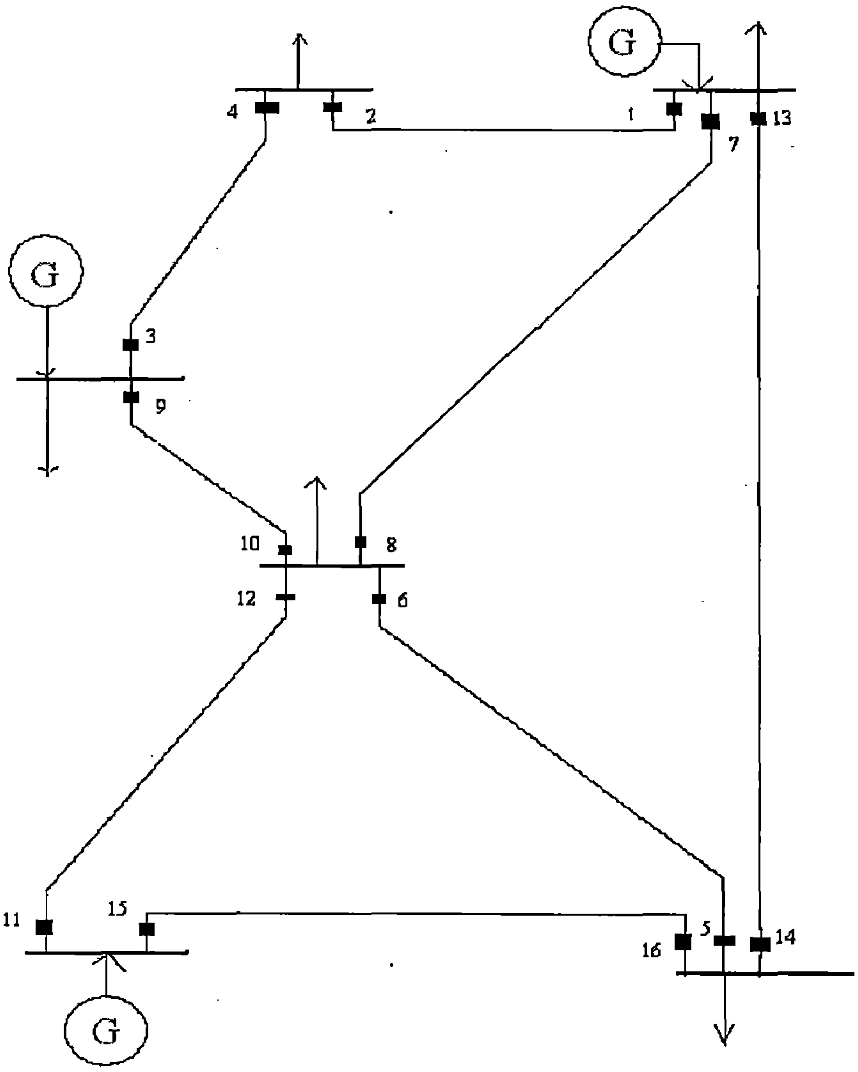


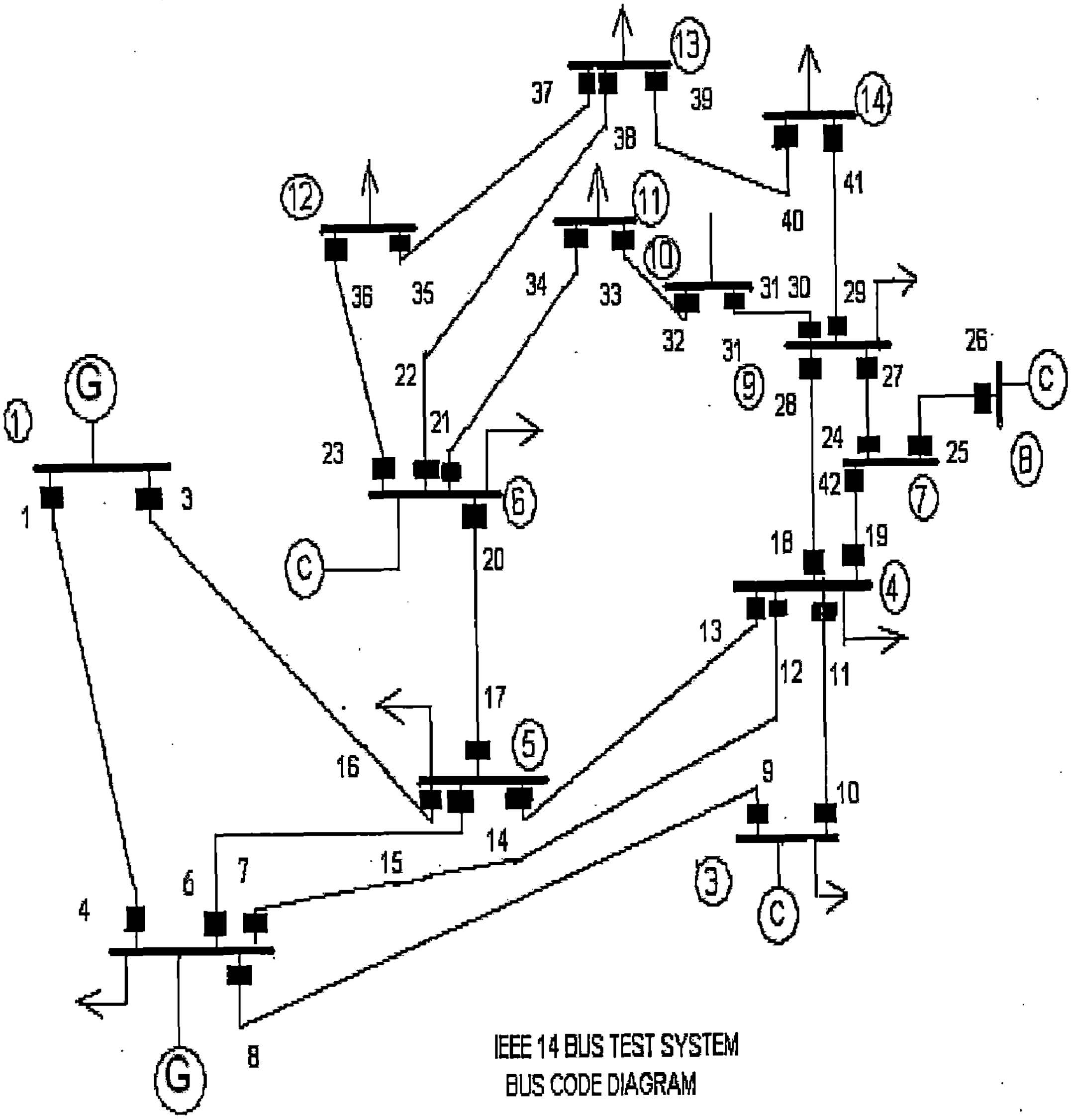
Figure A.1 6-BUS TEST POWER SYSTEM BUS CODE DIAGRAM

14-bus system: Bus data

BUS NO.	BUS TYPE	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPTANCE (P.U)
		MAGNITUDE (P.U)	ANGLE (RADIANS)	ACTIVE (MW)	REACTIVE (MVAR)	ACTIVE (MW)	REACTIVE (MVAR)	
1	3	1.0600	0.0000	231.136	-12.590	0.000	0.000	0.000
2	2	1.0450	-0.0866	40.000	42.000	21.700	12.700	0.000
3	2	1.0100	-0.2219	0.000	23.400	94.200	19.000	0.000
4	0	1.0078	-0.1774	0.000	0.000	47.800	3.900	0.000
5	0	1.0114	-0.1512	0.000	0.000	7.600	1.600	0.000
6	2	1.0500	-0.2488	0.000	12.200	11.200	7.500	0.000
7	3	1.0370	-0.2323	0.000	0.000	0.000	0.000	0.000
8	2	1.0500	-0.2323	0.000	17.400	0.000	0.000	0.000
9	0	1.0335	-0.2612	0.000	0.000	29.500	16.600	0.190
10	0	1.0288	-0.2642	0.000	0.000	9.000	16.600	0.000
11	0	1.0357	-0.2657	0.000	0.000	3.500	1.800	0.000
12	0	1.0347	-0.2814	0.000	0.000	6.100	1.600	0.000
13	0	1.0297	-0.2323	0.000	0.000	13.500	5.800	0.000
14	0	1.0134	-0.2814	0.000	0.000	14.900	5.000	0.000

14-bus system: Line data

LINE NO	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U)	LINE RATING
				RESISTANCE (P.U)	REACTANCE (P.U)		
1	1	1	2	0.0194	0.0592	0.0264	250.000
2	1	2	3	0.0470	0.1980	0.0219	125.000
3	1	2	4	0.0581	0.1763	0.0187	100.000
4	1	1	5	0.0540	0.2230	0.0246	125.000
5	1	2	5	0.0570	0.1739	0.0170	75.000
6	1	3	4	0.0670	0.1710	0.0173	50.000
7	1	4	5	0.0134	0.0421	0.0064	100.000
8	3	5	6	0.0000	0.2520	0.0000	75.000
9	3	4	7	0.0000	0.2091	0.0000	50.000
10	1	7	8	0.0000	0.1761	0.0000	25.000
11	3	4	9	0.0000	0.5562	0.0000	30.000
12	1	7	9	0.0000	0.1100	0.0000	50.000
13	1	9	10	0.0318	0.0845	0.0000	25.000
14	1	6	11	0.0950	0.1989	0.0000	25.000
15	1	6	12	0.1229	0.2558	0.0000	25.000
16	1	6	13	0.0662	0.1303	0.0000	25.000
17	1	9	14	0.1271	0.2704	0.0000	25.000
18	1	10	11	0.0821	0.1921	0.0000	25.000
19	1	12	13	0.2209	0.1999	0.0000	25.000
20	1	13	14	0.1709	0.3480	0.0000	25.000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IEEE 14 BUS TEST SYSTEM
BUS CODE DIAGRAM

Figure A.2

APPENDIX - B

STEEPEST DESCENT METHOD

The use of the negative of the gradient vector as a direction for minimization was first made by Cauchy. In this method we start from an initial trial point X_1 and iteratively move along the steepest descent directions until the optimum point is found. The steepest descent method can be summarized in the following steps:

1. Start with an arbitrary initial point X_1. set the iteration number as i=1
2. Find the search direction S_i as $S_i = -\text{grad}\,(f_i)$ where f is the objective function.
3. Determine the optimal step length P_i^* in the direction S_i and set

   $$X_{i+1} = X_i + P_i^* S_i$$

4. Test the new point, X_{i+1}, for optimality. If X_{i+1} is optimum, stop the process. Otherwise, go to step 5.
5. Set the new iteration number i = i + 1 and go to step 2.

The method of steepest descent is a good unconstrained minimization technique since each one-dimensional search starts in the best direction.

EXTERIOR PENALTY FUNCTION METHOD

Penalty function methods transform the basic optimization problem into alternative formulations such that numerical solutions are sought by solving a sequence of unconstrained minimization problems.

Let the basic optimization problem, with inequality constraints, be of the form:
Minimize f(X) subject to $g_j(X) <= 0$, j = 1,2,...,m

This problem is converted into an unconstrained minimization problem by constructing a function of the form

$$\phi(X, r_k) = f(X) + r_k \sum_{j=1}^{m} < g_j(X) >^q$$

Where rk is a positive penalty parameter, the exponent q is a nonnegative constant, and the bracket function $< g_j(X) >$ is defined as

$$< g_j(X) > = \max < g_j(X),\ 0 >$$

$= g_j(x)$;

$g_j(x) > 0$ (if constraint is violated)

Otherwise it is 0.

ALGORITHM

The exterior penalty function method is stated by the following steps:

1. Start from any design X_1 and a suitable value for r_1. set k=1.
2. find the vector X_k^* that minimizes the function

$$\phi(X, r_k) = f(X) + r_k \sum_{j=1}^{m} < g_j(X) >^q$$

3. Test whether the point X_k^* satisfies all the constraints. If X_k^* is feasible, it is the desired optimum and hence terminate the procedure. Otherwise go to step 4.
4. choose the next value of the penalty parameter that satisfies the relation

$$r_{k+1} > r_k$$

Subsequently set the new value of k as k+1 and go to step 2. Usually, the value of r_{k+1} is chosen according to the relation $r_{k+1} = c^* r_k$, where c is a constant greater than 1.