RELAY COORDINATION USING LINEAR PROGRAMMING METHOD FOR OPTIMAL SOLUTION

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

In

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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Undertaking for Originality of the Work

I, **Ms. Prutha P. Bhatt**, **Roll No:11MEEE01**, give undertaking that the Major Project entitled **"Relay Coordination using Linear Programming Method for Optimal solution"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Electrical Power Systems**, **Electrical Engineering** of Nirma University, Ahmedabad is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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CERTIFICATE

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Abstract

A modern power system is a wide and complex network comprises of countless interfacing control loops, transmission and distribution circuits along with the protection scheme. The prime role of protection scheme is to identify the nature of fault and to clear the fault within safe time frame to keep the power supply in all the network intact. The selected protection scheme affects the operating speed of the protection, which has a significant impact on the harm caused by fault condition. The faster the protection scheme operates, the smaller the resulting hazards, damage and the thermal stress will be.

Some statistical data indicates a large amount of relay tripping occurs mainly due to improper or inadequate relay setting over the occurrence of actual fault. Therefore it is of prime importance for power system engineers ti have a through knowledge of various protection scheme. The detail knowledge of various relay design, relay characteristics and control circuit of element which is to be protected is must that helps at various stages of design, erection, commissioning and maintenance. Detail study of protective relay and switchgear is inescapable to understand the procedure of actual relay setting in the practical scenario which play an important role in ensuring stable operation of electrical power system under normal and abnormal condition.

Thus, an optimization problem can be stated as selection of optimal settings of each relay which would minimize the operating time of relay. Various methods have been developed to find the optimal solution; the approach to have optimal solution can be exercised by several methods like Linear Programming (LP), Mixed Integer Programming (MIP),Simplex Method any a few more. Motivation of any of the method mentioned is to determine optimal selection of time dial setting and pick-up current which would minimize the operating time of protection scheme. Linear Programming method solves optimization problem with integration of MATLAB software with the help of the 'linprog' function of optimization toolbox. Implementation of linear programming on test system and standard system is exercised to fulfill the objective.

Linear programming technique can also be implemented only to minimize operating time while the pickup currents are selected based on experience. The work would mainly concern on overall findings, indicate that the linear programming using MATLAB can be used for investigation and improvement in order to identify which best technologies to be implemented.

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Abbreviations

DOCR .... Directional Over-current Relays
E/M .... Electro-Mechanical
GA .... Genetic Algorithm
GAMS .... General Algebraic Modeling System
LP .... Linear Programming
MNLP .... Mixed Integer Nonlinear Programming
MPSO .... Modified Particle Swarm Optimization
NLP .... Nonlinear Programming
OC .... Over Current
OCR .... Over Current Relay
OF .... Objective Function
PS .... Plug Setting
PSM .... Plug Setting Multiplier
RSM .... Relative Sequence Matrix
SSP .... Set of Selection Pairs
STI .... Selective Time Interval
TDS .... Time Dial Setting
TSM .... Time Setting Multiplier

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Chapter 1

Introduction

1.1 Background

Modern power systems seeks a large power rather energy demands and is spread over a wide area. The rapid growth of power sector compels us to expand supply network to bridge demand and generation. Therefore, economic and reliable design of supply network to provide uninterrupted electrical energy becomes essential which in-turn increases the pressure on the protection system strategy. Possibility of occurrence of abnormal condition is unescapable regardless of all the necessary precautions are taken at the stage of design and installation. In nature symmetrical fault is proved to be extremely severe to the equipment experiencing it but have an adverse impact on neighboring equipment also. It is advisable to limit the damage by fast operating device which isolates the faulty part of the system keeping rest of the system intact. An interruption of current in the desired path or flow of current in undesired path can be considered as a fault condition. Fast clearance of fault is required as consequences of fault may results into

- interrupted power supply at the consumer end
- interruption of service leads to revenue loss
- loss of synchronism
- equipment damage

- adverse impact on human life or personnel

The motivation of implementing protection scheme into power system is to identify the nature of the fault and quick removal of faulty part from the system to ensure the reliable system operation. Protection scheme is an integration of switchgear and protective relaying scheme. Relay is a device which senses the fault condition and issue a trip signal to circuit breaker to isolate the faulty part of the system.

A few decades before the calculation of time consumption for relay operation and setting of relay are used to be done manually. When computers were invented in early 60s, the scenario changed. A revolutionary change in relay setting calculation, design of relay, control scheme and performance analysis comes to a new era. Satisfactory coordination required several iterations of settings in early days. Eventually the trial and error method has adopted for setting protective relays in large network. Complex topological analysis programs had been developed to determine breakpoints set, pairs of relay to perform action for proper relay coordination in early days.

With the presence of error in setting of relays, development of justified mathematical model for over-current relay was essential. Mathematical implementation of relay characteristics became easy with the invention of computers in early 60s. It has offered an interactive graphical and analytical approach. In 1988, very first time optimization technique were implemented for relay coordination. Optimization technique does not require determination of breakpoints set and hence we can get rid out of complex topological analysis programs. Optimization techniques have gained popularity due to the fact that if offers optimal relay settings.

1.2 Problem Identification

The coordination problem in protective scheme can be expressed as the selection of fundamental protective function of relay under the various requirements like speed, selectivity, reliability and sensitivity. The task to select proper settings of the relay has always been difficult. Proper selection of time dial setting and pick-up current

setting altogether forms the over-current relay coordination. Proper coordination offers the correct sequential relay operation without deviating any limit and therefore it offers reliability to the system. Whenever fault current becomes equal or greater than the relay setting, the relay sends trip command to circuit breaker based on the adjustment of time dial setting.
Several conditions or situations makes relay coordination problem be more attentive and they can be described as

- The difficult task is to select the relay setting so that primary and back-up relay operates as they are planned in advance with fulfillment of the major requirements of the relay while implementing them into the system.

- Relay setting has been a difficult task when relays experiences different currents for the same fault when they are installed at different locations.

- Modern power system network is a quite complex network. The relay coordination problem seeks more attention when it is being implemented in multiloop system and multisource network to perform desirable and satisfactory operation.

Besides the optimal setting of time dial and pick-up current, an adequate time interval between operating time of primary and back-up relays should be opted. Selective time interval (STI) plays a critical role in proper relay coordination. Moreover the non-linearity of an objective function has to convert into a linear objective function.

Some mathematical model converts non-linear function into a linear function and solves the problem to obtain optimal solution. The parameters that determines the linearity of problem is pick-up current setting. The coordination problem is a linear programming problem for fixed value of pick-up current and coordination problem is a non-linear problem for continuous value of pick-up current.

Many optimization technique have been developed to work on relay coordination problem. Non-linear programming technique have more complexity, therefore the relay coordination problem should be formulated as a linear programming problem.

Linear programming technique may use simplex algorithm, dual simplex algorithm, infeasible interior point algorithm or two phase active set algorithm.

1.3 Objective of project

- To explore the scope of relay coordination in power system protection and incorporation of the linear programming method for relay coordination.
- To obtain the optimal value of time dial setting to keep the operation of the primary back-up relays coordinated with the help of linear programming method using real time data for different characterized over-current relays to prove its effectiveness for over-current line protection.
- To exploit the proposed scheme for standard IEEE9 bus system to have simplicity and versatility in its performance.

1.4 Scope of work

- The work will initiate with the relay coordination theory, and brief on over-current relays and its operation to have a better understanding on the system as a whole.
- The methodology will approaches to linear programming commencement and its features over other methods.
- Linear programming will be done to optimize the time dial settings of the relays tends to the considerations of coordination constraints and constraints for the relay settings.
- In MATLAB software this linear programming will be carried out with the help of the 'linprog' function of 'Optimization toolbox'.
- The approach will head to quantify the over-current relay settings by performing load flow analysis and short circuit studies on the network with the real time

data and then with the help of results obtained linear programming is applied and optimum results are expected to be achieved.

- The scientific approach will be extended for any of the standard bus system.(IEEE 9 bus or 14 bus)

1.5 Thesis Organization

Chapter 1 introduces the background of power system and conventional method to decide Time Dial Setting and plug setting multiplier, problem identification, Objective of project and Scope of work.

Chapter 2 gives literature survey which provides motivation to identify situations needing relay coordination and encouragement to implement Linear Programming method among several methods for relay coordination.

Chapter 3 provides fundamentals of Relay Coordination in power system, determination of Primary-Back-up relay and necessity of relay coordination. The chapter also covers the concept of Over-current relay, step by step approach for relay coordination and formulation of Objective function which is to be minimized.

Chapter 4 explains Interior Point method in Linear Programming and algorithm of Linear Programming for relay coordination. The chapter includes implementation of Linear Programming on IEEE9 bus system and test system with real time data using different relay characteristics and results obtained for the same.

Chapter 5 includes conclusion and future scope of proposed work.

Chapter 2

Literature Survey

In paper [1] an efficient method for optimal over-current relay coordination is proposed. A system consists of six pairs of short-circuit fault current for the fault very close to the circuit breaker is examined. To solve the said problem an objective function os prepared with the concept of genetic algorithm. Selection of primary/back-up relay pair is exercised based on fault location and algorithm of GA for the application of relay coordination is explained. In proposed method various relay characteristic coefficients are chosen to overcome the miscoordination problem for which total six cases are exercised and results are compared for all the six cases in context to relay operating time. Result indicates the coordination time interval which is greater than zero, miscoordination case where CTI is less than zero, an average of time dial setting of all the relays and an average of relay operating time. For the case in which six pairs of currents and final objective function is determined results in maximum miscoordinations and offers lowest operating time. The proposed methodology is applied on IEEE30-bus system to check which method results best, proposed one or conventional one.

A paper [2] narrates that the directional over-current relay (DOCR) may head to miscoordination under certain topologies like change in network configuration, maintenance activity and single line outage. The concept of linear programming can be developed for relay coordination for various network topologies with consideration of inequality constraints. The technique which is used in this paper is to convert the inequality constraints to their respective interval constraint. On modifying the inequality constraints, the coordination problem is represented as an inequality linear programming (ILP) problem with effectiveness of internal equality constraints. Results obtained from the exercise shows that internal method is proved to be robust and versatile to solve coordination problem of directional over-current relay against several topologies mentioned if, equality constraint is converted into a standard linear programming.

In paper [3] mathematical model of two phase simplex method is discussed to have optimal coordination time interval between primary and back-up relay. The paper explains primary/back-up relay coordination in ring fed system with the use of two phase simplex method. The statement of problem is formulated as an objective function which is to be minimized with consideration of certain constraints like, coordination criteria, relay characteristic, relay setting bound and operating time bound. Two phase simplex method is applied first on radial system and operating time of relay for the fault beyond the different buses is found. Later on the method is applied to distribution system having parallel feeders fed from one end and time dial setting of each relay is obtained with the use of proper selection of plug setting and C.T. ratio. As a result optimum time coordination between primary and back-up relay is obtained with the use of two phase simplex method.

A paper states [4] comparison between modified particle swarm optimization (MPSO) and genetic algebraic modeling system (GAMS) for 6-bus system. In this paper author has developed a flow-chart for MPSO technique and have used several solvers to solve non-linear problem in GAMS technique. Primary/Back-up relay pair, C.T. ratio for 6-bus system is selected and based on the fault current the results in-terms of time dial setting are obtained for both MPSO and GAMS. On comparing objective value with the accuracy of four decimal point, the MPSO is proved to be work properly for non-linear problem. Both the methods gives very close results even with accuracy of four decimal point, MPSO is proved versatile and successful to have optimal solution for non-linear programming problem (NLPP).

In paper [5] the necessity of linear programming to obtain feasible solution in-terms of time dial setting of objective function is stated. The setting of relay and the number of relays required to be reset comprises a tradeoff. No feasible point or solution is found if there is a tradeoff between primary and back-up relay coordination. Linear programming is applied on test system having six generators and 29 transmission line to form interconnected scheme. The selection of primary and back-up relay pair, C.T. ratio and pick-up current settings are done for linear programming to apply on test case system. The result embodies the time dial setting(TDS) of each relay for a given pick-up current and reduction in number of relays required to be reset.

A paper [6] states several relay settings as an optimization parameters. Relay characteristic, time multiplier setting(TMS) and pick-up currents of each relay are treated as an optimization parameters and each of them are formulated as a coordination problem to optimize them independently. The formation of problem is done in linear fashion. The author has developed a step by step method to select optimal pick-up current value, sequential steps to obtain optimal time characteristics and method to have optimal value of TMS. All the parameters of relays are optimized for 8-bus system and IEEE-30 bus network and result shows that rounding off the obtained setting can be avoided.

A paper [7] introduces a coordination problem for series compensated transmission line where combination of directional over-current relay and distance relay is incorporated. The author has developed a modified adaptive particle swarm optimization technique which is represented as non-linear and non-convex problem to solve the said coordination problem. The coordination problem becomes complex due to implementation of series capacitor into the transmission line as to coordinate between over-current relay and computation of optimal time of second zone relay is difficult task. New technique is applied on series compensated 8-bus system and semnan province grid to prove its effectiveness.

A paper [8] presents a formulation of a problem for coordination of microprocessor based directional over-current relays in an interconnected power system. Additional constrains are include to present the discrete nature of pick up current setting. In order to take into account the different relay time current curve, the relay characteristic constants are set as variables in formulation of problem. The main advantage of proposed formulation is its capability of determining the optimal relay settings as well as the optimal time current curves. In paper author have used DICOPT solver in GAMS to solve relay coordination problem as an MINLP problem.

The paper [9] has presented an approach based upon the minimize optimization approach to optimally coordinate protective relays in power systems. With the application of the proposed methodology, this coordination problem is stated as a non-linear parameter optimization problem that can be solved using conventional optimization techniques. The coordination problem was particularized to the case of directional over-current relays, and solved using direct optimization techniques, as well as several decomposition approaches and partitioning schemes. The paper demonstrates that the classical iterative procedure for solving the coordination problem of directional over-current relays is a solution which is limited to the minimization of a specific objective and which partitions the optimization problem into subproblems using a particular scheme to coordinate the subproblem solutions

A paper [10] introduces a few techniques and formulations to solve problem of directional over-current relay. In this paper mixed integer programming is introduced for directional over-current relay coordination. The nature of pick-up current setting is discrete due to addition of additional constraints to avoid non-linearity. The author states that knowledge of previous pick-up current setting does not require in formation of problem and the best objective value can be obtained from the pool of pick-up current settings. Methods like, NLP and MNLP may require elimination of generation of local optimal setting but the proposed method does not.

A paper [11] addresses the sum of time dial setting of relays as an objective function which is to be minimized. In this paper a problem is formed and solved by mathematical proof and simulation in software. The method called active set strategy two-phase method is used in linear programming to minimize operating times of relays when the value of pick-up current is predetermined. The said method focuses on finding time dial setting of each relay optimally so that the operation of primary/back-up relay is being coordinated. The author gives an importance on selection of C.T. in order to prevent the operation of system being miscoordinated.

Chapter 3

Relay Coordination

3.1 Introduction

Relay coordination is essential to obtain continuous operation of system, to obtain returns, to provide best maximum service to the consumer and earn the most revenue. Absolute freedom from the failure of the plant cannot be guaranteed, even though the risk of failure of each item may be low. The risk factors of such items, if multiplied together go high. Larger the system more will be the chances of the fault occurrence and disturbances due to the fault. Stages in fault clearance are

- occurrence of fault
- measurement by instrument transformer (CT/PT)
- analysis by protective relay for initiating selective tripping
- switchgear to clear the fault

Relay is only one part of protection chain in the protection system. For successful clearing fault

- CT must not be saturated
- CT and PT polarity must be correct
- Integrity of wiring between instrument transformers to relay should be alright

- Auxiliary supplies to the relay are available
- Relay characteristics are correct and set as per requirement
- compatibility between CT and relay
- Correct CB and CT installation
- Trip coil and trip circuit healthy
- CB tripping mechanism healthy
- Earthling should be correct

Relays are installed not to prevent the faults, but to sense the fault condition and to give trip command to circuit breaker to minimize the damage. Most of the relays act after damage has occurred. For good maintenance practice any substitute is not there rather sophisticated relays, correct relay setting and proper coordination.

3.2 Primary and Back-up protection scheme

Primary protection is essential protection provided for protecting an equivalent machine. As a precautionary measure an additional protection is generally provided and is called back-up protection. The primary protection is first to act and back-up protection is next in the line of defense, if primary protection fails ,the back-up protection comes into action and removes faulty part from the unhealthy system. Failures of the primary protection could be due to

- mal-operation of the relay
- improper installation or deterioration in service
- incorrect system design (e.g. CT saturation)
- wrong selection of the relay type
- circuit breaker failure (stuck breaker)

Back-up protection is provided for the following reason. If due to some reason, the main protection fails, the back-up protection serves the purpose of protection. Main protection can fail due to the failure of one of the components in the protective system such as relay auxiliary, CT, PT, trip circuit, circuit breaker etc. If the primary protection fails there must be an additional protection otherwise the fault may remain un cleared resulting in disaster. When main protection is made inoperative for the purpose of maintenance testing etc., the back-up protection acts like main protection. As a measure of economy, back up protection is given against short circuit protection and generally not for other abnormal conditions. The extent to which back up protection is provided depends upon economic and technical consideration.

3.3 Selection of Over-current Relay

An over-current relay has a single input in the form of ac current from secondary of C.T. Normally over-current relay lies in normally open state which changes over to normally close state when it gets actuated. Usually over-current relay offers two setting and they are time dial setting and plug setting. Operating time of relay is decided by time dial setting and current required for relay to actuate is decided by plug setting. An over-current relay may have either induction disc or induction cup type construction which depends on application and offers inverse time versus current characteristics.

Electromechanical relay offers an adjustable shorting plug in plug setting bridge which in turn changes the number of turns of operating coil of relay to have a desired pick-up value. In electromechanical over-current relay driving torque and restraining torque is offered by proper disc shape and permanent magnet having high retentivity. The most widely used characteristics in over-current relay is Inverse Definite Minimum Time (IDMT). IDMT offers inverness for small value of fault current and heads to definite minimum operating time with increase in fault current.

3.3.1 Features of Over-current Relay

- Offers identical time versus current characteristics on available taps.
- Does not require any separate auxiliary supply to perform action.
- Comprehensive range of high-set unit ratings.
- Offers high torque on actuating value.
- Comparatively less overshoot time.
- Simple in construction and be accessed easily for any maintenance work.

Over-current relay can be characterized as Inverse Over-current, Inverse Definite Minimum Time, Very Inverse Time, Extremely Inverse Time. The operating time of each relay depends on TDS, PSM and constants. Operating time for each relay can be given by

Inverse Over-current

$$T_{op} = \frac{0.14 \times TDS}{[PSM^{0.04} - 1]} \tag{3.1}$$

Inverse Definite Minimum Time Over-current

$$T_{op} = \frac{0.14 \times TDS}{[PSM^{0.02} - 1]} \tag{3.2}$$

Very Inverse Time Over-current

$$T_{op} = \frac{13.5 \times TDS}{[PSM - 1]} \tag{3.3}$$

Extremely Inverse Time Over-current

$$T_{op} = \frac{80.0 \times TDS}{[PSM^2 - 1]} \tag{3.4}$$

Where PSM can be defined as ratio of fault current to pick-up current. PSM = $\frac{I_f}{I_p}$

In the power system during fault the back up relay also should provide time for primary relay to operate. This time interval is known as Coordination Time Interval and this process is known as Relay Coordination.

3.4 Necessity of Relay Coordination

Sequential operating action when two or more protective relays are installed to protect any electrical equipment is said to be coordinated or selective. Some other requirements like speed, reliability and sensitivity should also met the sequential operating action. Adequate time interval between the operating times of protective relays to ensure correct sequential operation must be maintained. The operating principle offers adequate chance to primary protection if any fault condition takes place under its protective zone. Only if primary protection fails to perform action, tripping should be initiated by back-up protection. In general fault should be sense by primary protection first and progression should be switched on to the back-up protection.
Several factors compels to exercise about relay coordination are

- Task to design a protection scheme on transmission line of power network is difficult.
- A relay works as a primary relay if fault lies in its primary protection zone and same has to work as a back-up if fault is in other than its primary protection zone.
- A relay should identify or discriminate the correct fault location to act as a primary protection or back-up protection and hence relay appeals proper selectivity.
- Variety of setting procedure and relaying schemes are offered by different utilities. A small change in relay setting may affect the system relaying scheme. Therefore relay coordination is defined as the problem of coordinating protective relay problem in power system

Aim to protect transmission line with directional over-current relay is to minimize the operating time of relay with appropriate relay setting. In power system during fault the back up relay should also provide time for primary relay to operate this time interval is known as "Coordination Time Interval" or "Selective Time Interval " and this process is known as "Relay Coordination". Relay coordination can be done by selecting proper plug setting and time dial setting.

3.4.1 Steps for Relay Coordination

- Step 1: Calculate full load current. In practice calculation of full load current have prime importance over normal rated current. To have full load current one has to perform load flow study on given system.

- Step 2: Calculate short circuit current with the help of available data. In practice calculation of fault MVA is determined and based on that symmetrical or unsymmetrical fault current is calculated. Symmetrical short circuit gives the severe fault current among any type of fault. Severity of fault helps in deciding C.T. ratio so that under severe fault condition C.T. does not go in saturation state.

- Step 3: Relay operating characteristic is an important consideration. Many a times over-current relay may malfunction when transformer and motor draws more inrush current and hence dynamic operating characteristic of relay is determined in addition with consideration of full load current.

- Step 4: Proper selection of pick-up current of relay. Selection of pick-up current mainly depends on location of fault, location of equipment and safety margin. Selection of pick-up setting changes for different cases to have proper coordination.

- Step 5: Determination of coordination time interval. Coordination time interval constitutes circuit breaker operating time, relay operating time and relay overshoot time in case of electromechanical relay. Coordination time interval between primary and back-up relay should be minimum but adequate enough.

- Step 6: Selection of appropriate C.T. ratio. Improper C.T. ratio may lead to miscoordination action. In order to avoid deep saturation of C.T. proper selection of C.T is necessary for accurate protection action.

- Step 7: Selection of setting range available. Microprocessor or numerical relay offers wide setting range over electromechanical or static relay.

The following flow chart[13] gives an idea about step by step method for relay coordination.

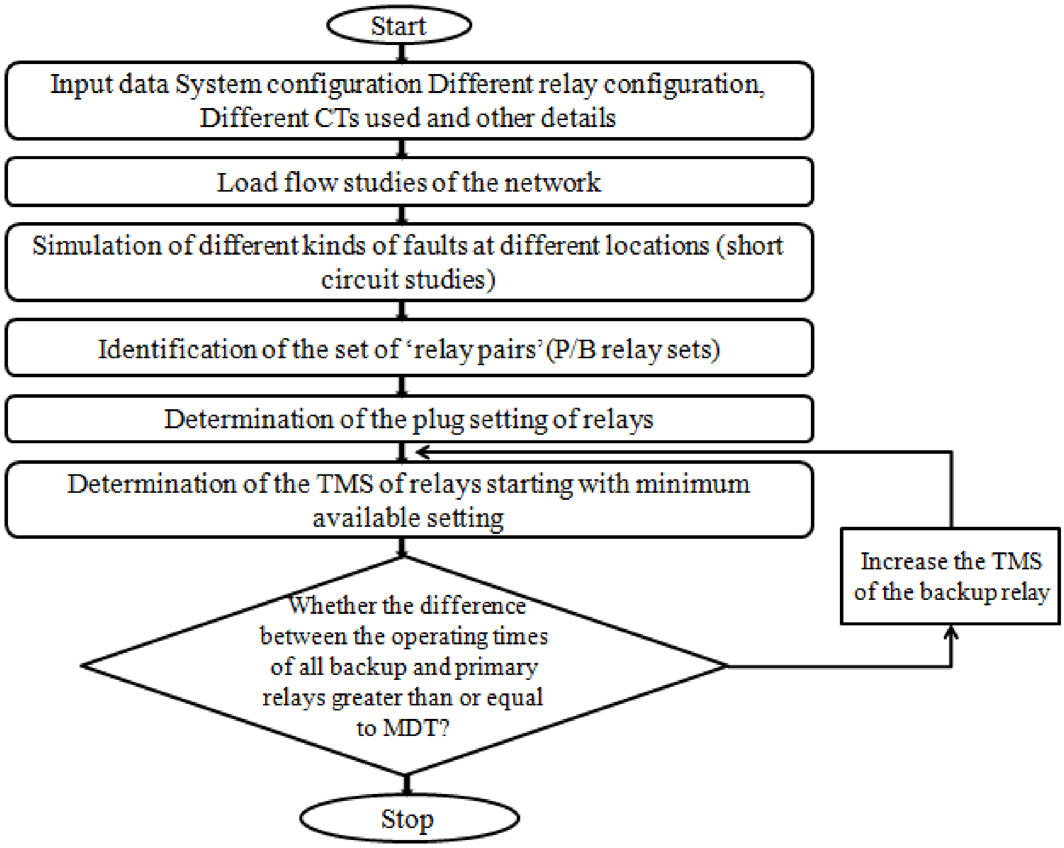

Figure 3.1: Generalized flow chart for Relay Coordination

3.4.2 Discrimination Time (Coordination Interval)

This refers to the time interval between the operation of two adjacent breakers or breaker and fuse. Factors affecting Discrimination Time are

a. Coordination interval shall incorporate the following time periods

- Interrupting time of breaker
- relay error factor(Refers to negative or positive errors in operating time of the relays/fuse involved in grading.)
- For coordination time between fuse & breaker(if any)

- For coordination time between breaker & breaker

b. Overshoot time of relay(if relay is electromechanical type)

c. Safety Margin

The maximum pick up current is selected in such a way that,

- The selection is less than the least value of fault current which relay senses.
- The minimum time discrimination obtain lastly is about 0.20 seconds.
- This problem can be formulated in various programming software.

3.5 Determination of Objective Function

The coordination problem of directional over-current relays in interconnected power systems, can be treated as an optimization problem in which the sum of the operating times of the relays of the system is to be minimized, tends to the following constraints

- Coordination criteria
- Bounds on relay settings
- Bounds on operating times
- Operating relay characteristics

Thus optimization problem can be formulated as

$$min \sum_{i} \sum_{j} T_{ij} W_{ij} \tag{3.5}$$

tends to

a. h(T)$\leq$ 0 (Coordination Criteria)

b. $S_{min}$$\leq$S$\leq$ S_{max} (bounds on the relay setting)
$T_{min}$$\leq$T$\leq$ T_{max} (bounds on the operation time)

c. T = f(s)

where T_{ij} is the operating time of relay i of branch j and W_{ij} is the weighting factor assigned to the respective relay.

Coordination Criteria

h(T)$\leq$ 0, which for a given configuration can be described by

$$T_{nm} \geq T_{ij} \Delta T_{mj} \tag{3.6}$$

where T_{nm} represents the operating time of the first back-up of R_{ij} for a fault in particular protection zone and ΔT_{mj} is the selective time interval for zones m and j. This coordination time interval depends upon the operation times of the power circuit breakers, the operation criteria, and other system parameters.

Bounds on relay setting and operating time

$$TDS_{ijmin} \leq TDS_{ij} \leq TDS_{ijmax} \tag{3.7}$$

$$I_{pijmin} \leq I_p \leq I_{pijmax} \tag{3.8}$$

$$T_{ijmin} \leq T_{ij} \leq T_{ijmax} \tag{3.9}$$

Where, TDS_{ij} represents the time dial setting of relay R_{ij}, I_{pij} is nothing but the pick-up current of relay R_{ij}, and I_{ij} is the current seen by relay R_{ij} for a fault in a particular location.

Relay Characteristics

$$T = f(TDS, I_p) \tag{3.10}$$

Optimal Selection of Time dial setting

The optimal coordination problem of directional over-current relays is treated as non-linear optimization problem (for fixed I_p) due to the fact that the time dial settings TDS are related to the operation times T_{ij} in a non-linear 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 the over-current relays are represented by characteristics of the type indicated in eq.(3.10) with known value of pick-up current. In this case, the equation for relay operating time can be rewritten in the following form which relates TDS and T_{ij} linearly as

$$T_{ij} = k_{ij} TDS_{ij} \tag{3.11}$$

Where,

$$k_{ij} = \frac{k_1}{[(\frac{I_{ij}}{I_{pij}})^{k_2} \pm k_3]} \tag{3.12}$$

Normally the directional over-current relay comprises of two different characterized units out of which one is an instantaneous unit which is time independent and another is an inverse over-current unit which is time dependent. The relay actuates on the least current value from C.T secondary is considered as pick-up value of relay. The time dial setting defines the operating time of the relay and is generally given as a curve, T versus M, where M is a multiple of the pick-up current, i.e. M $= \frac{I}{I_{pu}}$, and I is the relay current.

$$T = \frac{k_1 \times TDS}{M^{k_2} - 1} \tag{3.13}$$

where, k_1 and k_2 are relay constants which depends on the relay characteristic (inverse, very inverse, extremely inverse, etc.). Relay constants k_1 and k_2 for different relay characteristics are mentioned in equation 3.1, 3.2, 3.2 and 3.4. Over-current relays offers discrete pick-up current settings and continuous time dial setting.

3.5.1 Statement of the proposed formulation

The relay coordination problem can be treated as a parametric optimization problem. The objective function of optimization problem is to minimize the operating time of primary relay with consideration of operation of back-up relay intact. The objective can be fulfilled by one possible approach where we can minimize a sum of the operating times of all primary relays subject to the operating times of individual primary relays would be achieved close to the minimum individual operating times. The objective function J which is to be minimized can be expressed as

$$J = \sum_{i=1}^{n} T_{ii} \tag{3.14}$$

where, T_{ii} is primary relay R_i operating time relay for a fault near to relay R_i. The operating time of the back-up relay R_j which would have act in failure of primary relay R_i must be greater than the sum of the operating time of primary relay R_i and the coordination margin. The same can be expressed as

$$T_{ji} = T_{ii} + CTI \tag{3.15}$$

where, T_{ji} can be expressed as the operating time of the back-up relay R_j for the same fault close to the relay R_i and CTI is the coordination/selective time interval. Correlation between the operating time of over-current relay and multiple of pick-up current is seems to be non-linear. For predetermined value multiple of pick-up current i.e. for a constant M, equation 3.13 becomes linear and which can be expressed as follows

$$T = a \times TDS \tag{3.16}$$

where,

$$a = \frac{k_1}{M^{k_2} - 1} \tag{3.17}$$

By substituting the value of operating time in equation (3.14), the objective function becomes

$$J = \sum_{i=1}^{n} a_i \times TDS_i \tag{3.18}$$

where a_i in equation 3.18 have effect on the optimal solution as it inversely proportional to ratio of fault current and pick-up current of relay and changes with relay constants. The value of TDS is determined by minimizing the objective function expressed in equation 3.14 keeping the coordination between the primary and back-up relay intact. Equation (3.14) can be optimized using the well-known Infeasible Interior Point method tends to the operation of the back-up relays remains properly coordinated.

Chapter 4

Linear Programming for Relay Coordination

4.1 Introduction

This section describes implementation of a primal-dual infeasible interior point algorithm for large scale linear programming under the MATLAB environment. The resulting algorithm is called **LIPSOL**, **L**inear-programming **I**nterior-**P**oint **SOL**ver. LIPSOL is designed to take the advantages of MATLAB's sparse-matrix functions and external interface facilities. Under the MATLAB environment LIPSOL inherits a high degree of simplicity and versatility in comparison to its counterparts in Fortran or C language.
Among many general algorithmic approaches, the most effective one in practice has proven to be the primal dual infeasible interior point approach including a number of variants and enhancements such as Mehrotra's predictor corrector technique.

The flow chart shown in fig 4.1 gives steps to determine END, NEXT, LIST and FAR vectors used in determination of primary/back-up pair to perform coordination exercise.

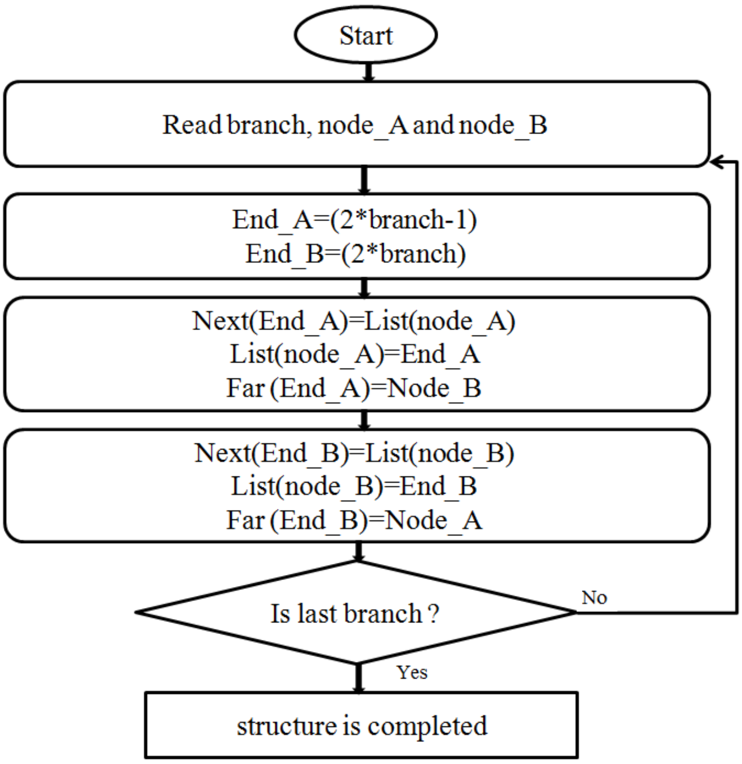

Figure 4.1: Flowchart of LINKNET structure

4.2 Procedure for Relay Coordination using LP

- To formulate problem of relay coordination we have to prepare programme for it. In this first we have to represent a network in computer and this can be done by LINKNET structure [13].
- After this our next step is to find the PRIMARY BACK-UP relay pairs.[13] This is very important to select because if we missed out one back-up relay, it would lead to mal-operation elsewhere in the network.
- There are three one dimensional vectors used in it namely LIST which represent bus of the system, NEXT represents nearest relay to the bus and FAR represents farthest relay from that bus.
- After this we have to do a load-flow studies of the system and find out maximum full load current flowing from each line. Line contingencies are also required to be considered.

- After this load flow analysis we can find the plug setting of the relay.
- In next we have to do a short circuit calculation.
- After this we have to make sure that all the relays were considered or not. Now after this we have to input data in the programme as per requirement.
- After input data, run program and we get the relay coordination process results in the form of primary back-up relay relay operating time and TDS of each relay.

AIM of this programming is to calculate and find TDS which would minimize the time of operation of the relays.

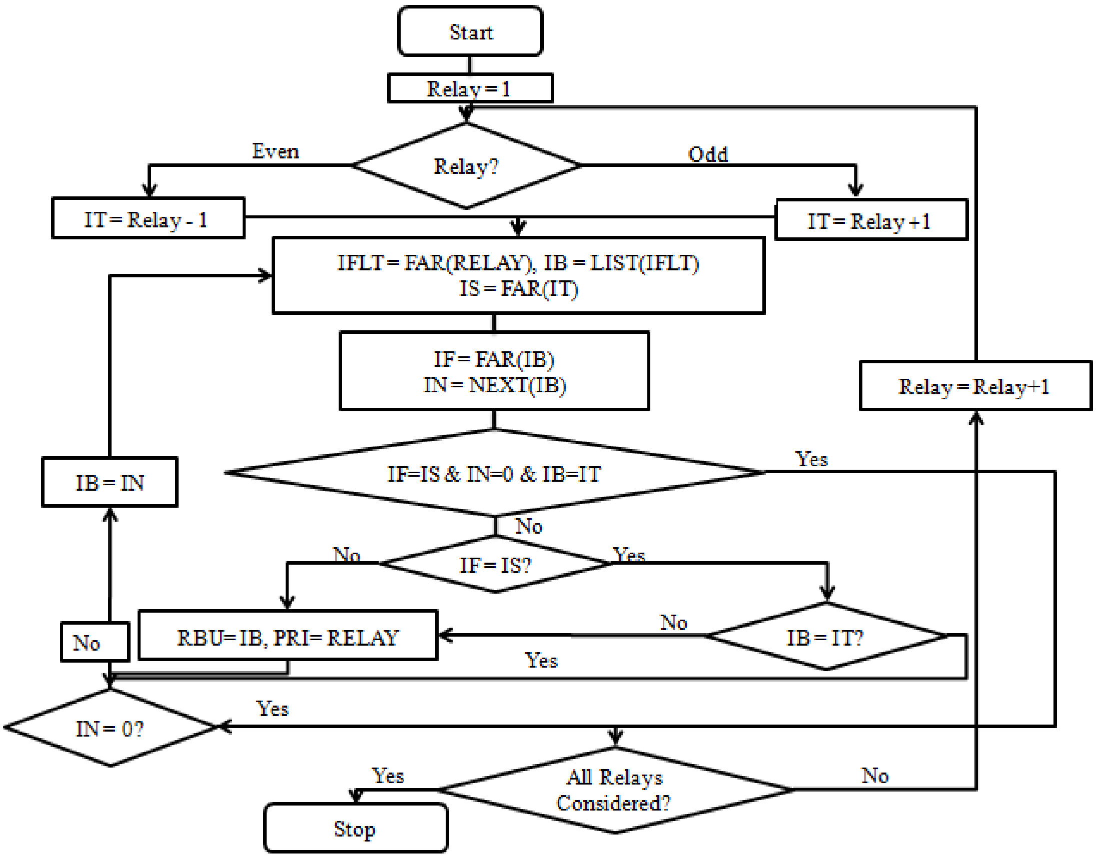

Figure 4.2: Flowchart for Primary/Back-up pair determination

4.3 Test System Configuration

For incorporation of linear programming method a test system is taken which consists of three generator of same rating, six buses and three transmission line to have a interconnected system. All the parameters taken are the real system parameter and hence based on results obtained we do expect implementation of linear programming for real system.

In practice, normally the long transmission line has been protected by distance relays rather than over current relays hence the concept of linear programming for over-current relay can not be implemented for protection of long transmission line.

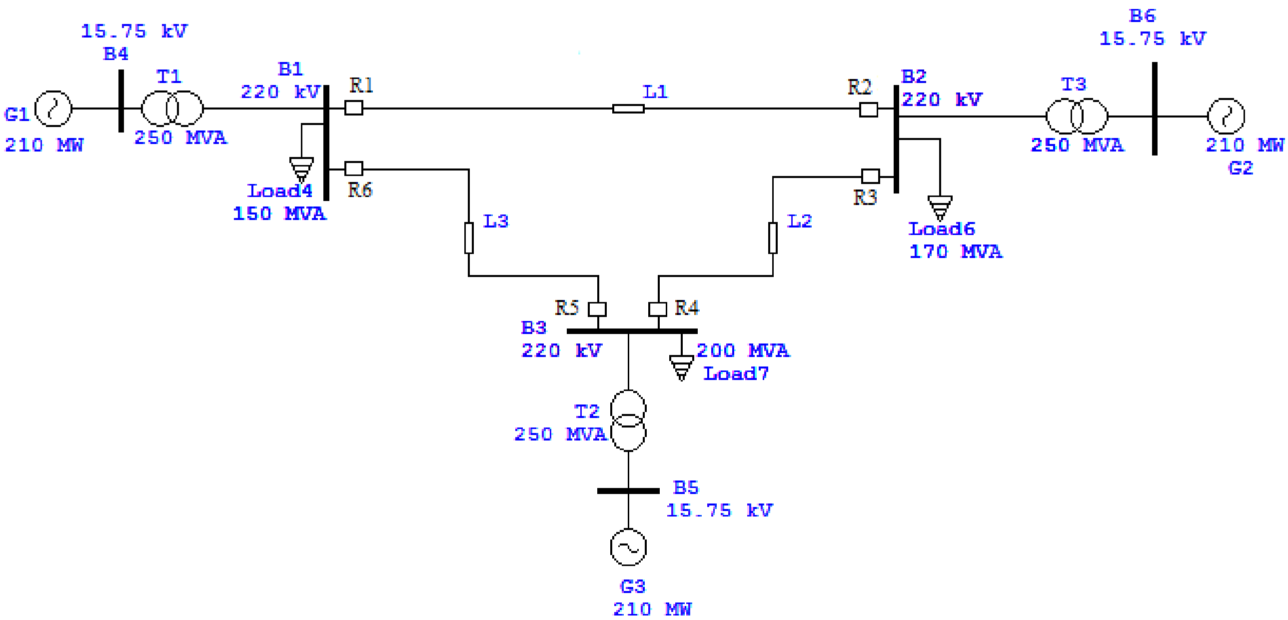

Figure 4.3: SLD of test system

4.3.1 Primary back-up relay pairs

It is essential to determine primary/back-up relay pair before proceeding to load flow analysis as the objective is to have optimal coordination between primary and back-up relay. The flowchart in fig 4.2 gives steps rather procedure to find primary-back-up relay pair. The exercise is done for test system with real time data and primary-back-up relay pair is obtained shown in table below.

Table 4.1: Primary/Back-up relay pairs for test system

Primary Relay	Back-up Relay
1	5
2	4
3	1
4	6
5	3
6	2

4.4 Load flow solution of test system

After determining relay pair next step is to perform load flow analysis which gives an idea about normal rated current flow in all the transmission line. Based on the normal rated current under full load condition C.T. ratio is decided. Load flow using Newton-Raphson method is performed on test system in ETAP software.

Table 4.2: Load flow results of test system

From bus	To bus	Voltage Magnitude(%)	Angle	MW	MVAR	Amp
Bus 1	Bus 2	95.917	-9.7	168.40	-12.14	461
Bus 1	Bus 3			120.65	-5.24	330
Bus 1	Bus 4			-406.35	-55.32	1122
Bus 2	Bus 1	95.752	-10.0	-168.04	13.05	461
Bus 2	Bus 3			35.47	6.55	98
Bus 2	Bus 6			0.09	-101.70	278
Bus 3	Bus 2	95.712	-10.1	-35.46	-6.52	98
Bus 3	Bus 1			-120.36	5.98	330
Bus 3	Bus 5			0.08	-95.98	263
Bus 4	Bus 1	100	0.0	407.81	128.43	15672
Bus 5	Bus 3	100	-10.1	0.0	100.00	3675
Bus 6	Bus 2	100	-10.1	0.0	106.21	3893

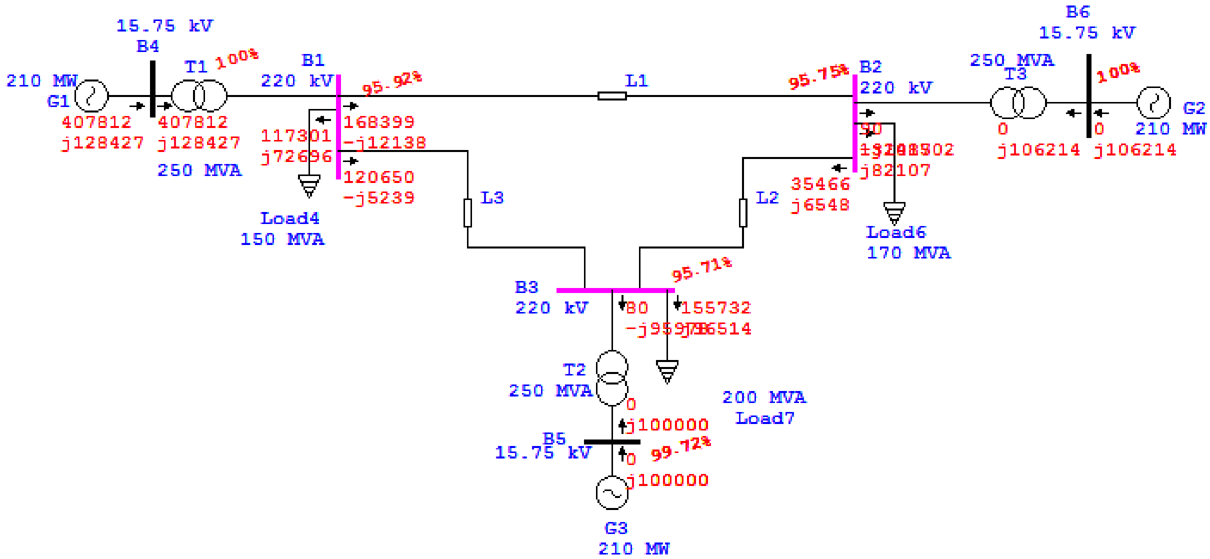

Figure 4.4: Load flow analysis of real system

4.4.1 Selection of C.T.

The current transformer can be selected according to the maximum load current but it must not saturate at high fault currents. The secondary current value of the CT must not overreach 20 times the selected CT current rating otherwise, the CT will be saturated and consequently, the protective relaying system will not operate, or operate improperly.

Table 4.3: Load current and C.T. Ratio of test system

From bus	To bus	Relay No.	Load current (A)	C.T. Ratio	Plug Setting(%)
1	2	R1	461	800:1	63
1	2	R2	-	800:1	63
2	3	R3	98	200:1	53
2	3	R4	-	200:1	53
3	1	R5	330	800:1	45
3	1	R6	-	800:1	45

4.5 Implementation of proposed methodology

The linprog function solves the non linear problem

$$\mathrm{A}\times\mathrm{x} \leq \mathrm{b},$$

$$A_{eq}\times\mathrm{x}=b_{eq}$$

$$\mathrm{lb} \leq \mathrm{x} \leq \mathrm{ub}$$

$$\mathrm{A}\times\mathrm{x} \leq \mathrm{b} \text{ can be represented as } \text{-}\mathrm{A}\times\mathrm{x} \geq \text{-}\mathrm{b},$$

where A is Relay operating time, x represents TDS(Time Dial Setting) and b represents coordination time interval.

- -(Back-up relay operating time- Primary relay operating time)$\times$x $\geq$ -b,
- equals to (Primary relay operating time- Back-up relay operating time)$\times$x $\geq$ -b

The problem of determining the optimal TDSs and consequently the minimum operating times, for the close-in faults of the relays of this system can be formulated as the following linear programming problem;

$$\mathrm{Min\ J} = \mathrm{T1+T2+T3+T4+T5+T6}$$

Subject to the following constraints:

$$\mathrm{T1\text{-}T5} \geq -0.2$$

$$\mathrm{T2\text{-}T4} \geq -0.2$$

$$\mathrm{T3\text{-}T1} \geq -0.2$$

$$\mathrm{T4\text{-}T6} \geq -0.2$$

$$\mathrm{T5\text{-}T3} \geq -0.2$$

$$\mathrm{T6\text{-}T2} \geq -0.2$$

4.5.1 LP for relay coordination

Results obtained for IOC relay from LP

Linear Programming is applied on test system using fault current and pick up current of relays for close in fault. By performing linear programming the results obtained

Table 4.4: Primary/Back-up Relay operating time for IOC relay

Primary Relay No	TDS	Operating time(Sec.)	Back-up Relay No	TDS	Operating time(Sec)
1	0.1000	0.2418	5	0.1524	0.4416
2	0.1797	0.3109	4	0.1197	0.5109
3	0.1190	0.3034	1	0.1000	0.5109
4	0.1197	0.3114	6	0.1187	0.5113
5	0.1524	0.2731	3	0.1190	0.4733
6	0.1187	0.2484	2	0.1797	0.4484

in terms of TDS and operating time are as follows. By substituting the values of the short circuit and pick-up currents in equations yields

Min [2.4180×TDS1+1.7305×TDS2+2.5502×TDS3+2.6022×TDS4+1.7926×TDS5 +2.0927×TDS6]= 1.6894 Subject to,

$$2.4180\times TDS1-2.8978\times TDS5 \geq -0.2$$
$$1.7305\times TDS2-4.2684\times TDS4 \geq -0.2$$
$$2.5502\times TDS3-5.1096\times TDS1 \geq -0.2$$
$$2.6022\times TDS4-4.3081\times TDS6 \geq -0.2$$
$$1.7926\times TDS5-3.9776\times TDS3 \geq -0.2$$
$$2.0927\times TDS6-2.4956\times TDS2 \geq -0.2$$
$$\text{and } 1.1 \geq TDS \geq 0.1$$

The Optimization is terminated after 8 iterations.

Results obtained for IOC relay from LP

The results obtained in table 4.4 are for Inverse Over-current relays. The same can be exercised for IDMT over-current relay where invernesses and definite time characteristics are required to be exploited. Operating time of IDMT relay can be defined as

$$t_{op} = \frac{0.14}{[PSM^{0.02} - 1]} \times TDS \tag{4.1}$$

Min [2.4180×TDS1+1.7305×TDS2+2.5502×TDS3+2.6022×TDS4+1.7926×TDS5 +2.0927×TDS6]= 2.8266. Results obtained with implementation of IDMT relays in

Table 4.5: Primary/Back-up Relay operating time for IDMT relay

Primary Relay No	TDS	Operating time(Sec.)	Back-up Relay No	TDS	Operating time(Sec)
1	0.1000	0.4905	5	0.1177	0.6904
2	0.1236	0.4362	4	0.1000	0.8606
3	0.1000	0.5169	1	0.1000	1.0288
4	0.1000	0.5273	6	0.1000	0.8685
5	0.1177	0.4300	3	0.1000	0.8024
6	0.1000	0.4254	2	0.1236	0.6254

system are shown in table 4.5.**The Optimization is terminated after 9 iteration.**

4.6 IEEE9 Bus system Configuration

The Load flow analysis of IEEE 9-bus test system is performed on ETAP. The single line diagram (SLD) of the simulated test system on ETAP is shown in Fig 4. For

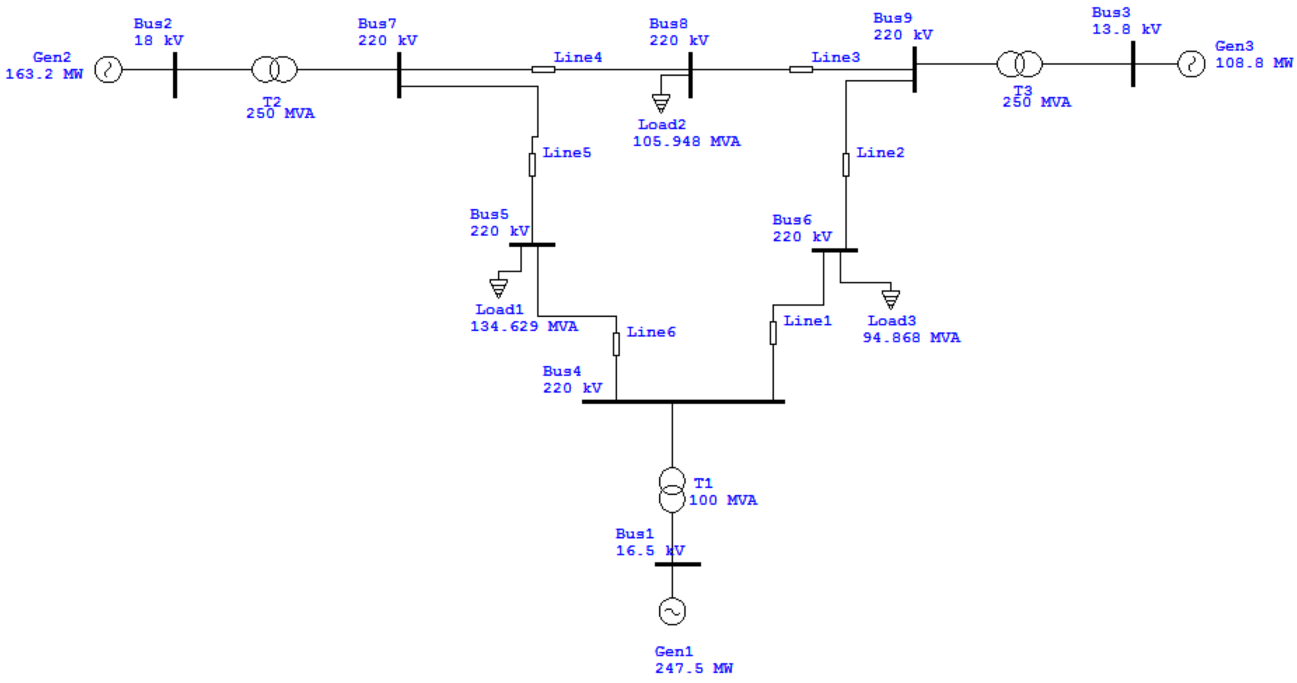

Figure 4.5: SLD of IEEE9 Bus System

this test system generator and line parameters are given in appendix. The total generation is 519.5MW and total load is 315MW. The standard system contains 6 lines connecting the buses to form interconnected system. The generator is connected to network through step-up transformer at 220kV transmission voltage. The results of load flow analysis when all generators and loads are operating at rated power is to be obtained.

4.6.1 Selection of Primary/Back-up relay pairs

It is essential to determine primary and back-up relay pair before proceeding to load flow analysis as the objective is to have optimal coordination between primary and back-up relay. The flowchart in fig 4.2 gives steps rather procedure to find primary/back-up relay pair. The exercise is done for test system with real time data and primary/back-up relay pair is obtained shown in table below.

Table 4.6: Primary/Back-up relay pairs for IEEE9 bus system

Primary Relay	Back-up Relay	Primary Relay	Back-up Relay
1	3	7	9
2	12	8	6
3	5	9	11
4	2	10	8
5	7	11	1
6	4	12	10

4.7 Load flow solution of IEEE9 bus system

Load flow analysis has to apply once primary/back-up relay pair is decided. Load flow analysis gives an idea about active and reactive power flow in system, voltage magnitude and angel at particular bus, based on these information we can calculate or determine normal rated current flow in all the transmission lines. Based on the normal rated current under full load condition, C.T. ratio is decided. Load flow can be performed with several conventional technique e.g. Newton-Raphson, Fast Decoupled and Accelerated Gauss-Seidel method. Load flow study on IEEE9 bus system using Newton-Raphson method is performed in ETAP software. The figure

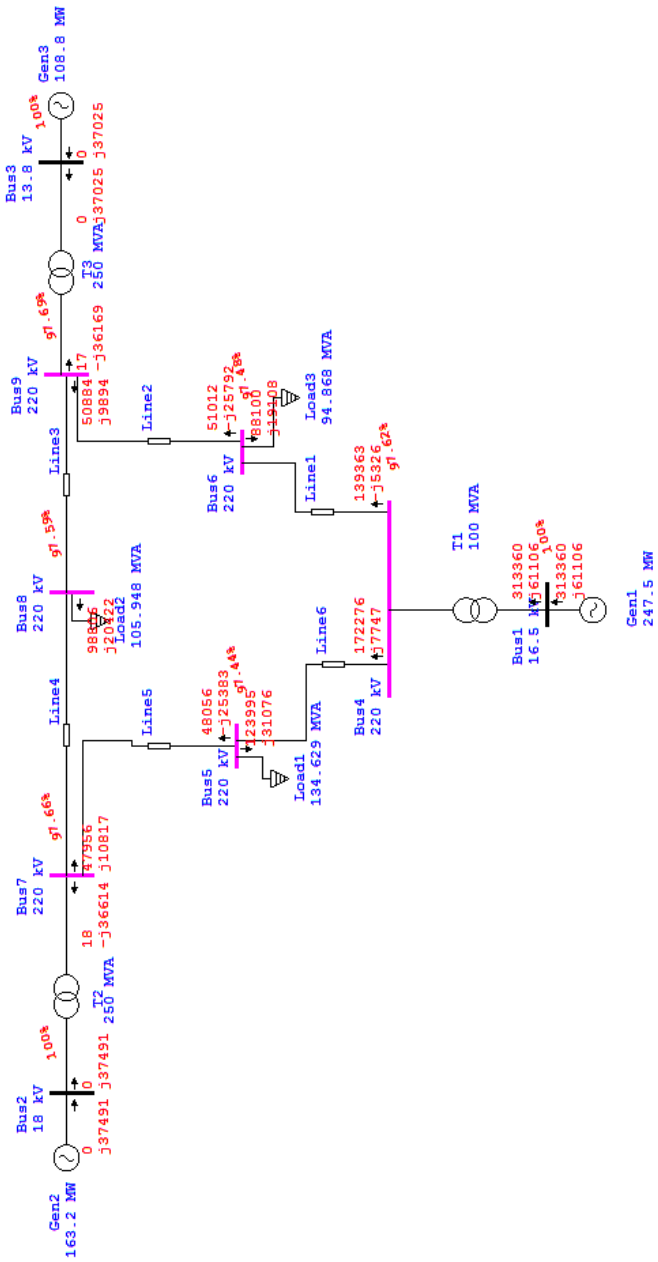

Figure 4.6: Load flow analysis of IEEE9 bus system

4.6 indicates power flow in each transmission line, indication of loading of bus & percentage voltage magnitude on each bus. The dash sign (-) in table 4.8 refers that the relay which is insensitive in this direction of the current flow, in case of overload,

Table 4.7: Load flow results of IEEE9 bus system

From bus	To bus	Voltage Magnitude(%)	Angle	MW	MVAR	Amp
Bus 1	Bus 4	100	0.0	313.36	61.11	11171
Bus 2	Bus 7	100	-11.7	0.0	37.49	1202
Bus 3	Bus 9	100	-11.7	0.0	37.03	1549
Bus 4	Bus 6	97.61	-10.60	139.36	-5.33	374
Bus 4	Bus 5			172.28	7.75	463
Bus 4	Bus 1			-311.64	-2.42	837
Bus 5	Bus 7	97.442	-11.3	48.06	-25.38	146
Bus 5	Bus 4			-172.05	-5.69	436
Bus 6	Bus 4	97.48	-11.2	-139.11	6.68	374
Bus 6	Bus 9			51.01	-25.79	153
Bus 7	Bus 8	97.66	-11.7	47.96	10.82	132
Bus 7	Bus 5			-47.97	25.80	146
Bus 7	Bus 2			0.02	-36.61	98
Bus 8	Bus 9	97.568	-11.8	-50.86	-9.72	139
Bus 8	Bus 7			-47.94	-10.70	132
Bus 9	Bus 6	97.687	-11.6	-50.90	26.28	153
Bus 9	Bus 8			-50.88	9.89	139
Bus 9	Bus 3			0.02	-36.17	97

and the directional unit will restrain the relay operation. This relay will be sensitive if the current inverses its direction, in case of fault current flow.

4.7.1 Selection of C.T.

Once the load flow analysis is done the next step is determine CT ratio and Plug Setting of the relay. Load flow analysis gives the normal current flows in each transmission line under full load condition. In practice the C.T. ratio is determined considering safety factor. Selection of C.T. plays an important role in protection as the output of C.T. is input to relay. C.T. should be selected in such a way that it does not go in saturation state even at severe fault condition. The secondary current value of the CT must not overreach 20 times the selected CT current rating otherwise, the CT will be saturated and consequently, the protective relaying system will not operate, or operate improperly.

In reference to overload condition we determine plug setting(pick-up current) of the relay either in Amp or in percentage.

Table 4.8: Load current and C.T. Ratio of IEEE9 bus system

From bus	To bus	Relay No.	Load current (A)	C.T. Ratio	Plug Setting(%)
4	6	R1	374	800:1	51
4	6	R2	-	800:1	51
6	9	R3	153	400:1	42
6	9	R4	-	400:1	42
9	8	R5	139	400:1	38
9	8	R6	-	400:1	38
7	8	R7	132	400:1	36
7	8	R8	-	400:1	36
5	7	R10	146	400:1	40
5	7	R9	-	400:1	40
4	5	R12	463	800:1	63
4	5	R11	-	800:1	63

4.8 Implementation of LP on IEEE9 bus system

The linprog function solves the non linear problem

$$\mathrm{A}\times\mathrm{x} \leq \mathrm{b},$$

$$A_{eq}\times\mathrm{x}=b_{eq}$$

$$\mathrm{lb} \leq \mathrm{x} \leq \mathrm{ub}$$

$$\mathrm{A}\times\mathrm{x} \leq \mathrm{b} \text{ can be represented as } -\mathrm{A}\times\mathrm{x} \geq -\mathrm{b},$$

where A is Relay operating time, x represents TDS(Time Dial Setting) and b represents coordination time interval.

- -(Back-up relay operating time- Primary relay operating time)×x ≥ -b,
- equals to (Primary relay operating time- Back-up relay operating time)×x ≥ -b,

which can be observed as $T_{back-up}$-$T_{primary}$≥0.2 or $T_{primary}$-$T_{back-up}$≥-0.2
By substituting the values of the short circuit and pick-up currents in equations yields

Subject to the following constraints:

$$T3 - T1 \geq 0.2 \qquad T9 - T7 \geq 0.2$$
$$T12 - T2 \geq 0.2 \qquad T6 - T8 \geq 0.2$$
$$T5 - T3 \geq 0.2 \qquad T11 - T9 \geq 0.2$$
$$T2 - T4 \geq 0.2 \qquad T8 - T10 \geq 0.2$$
$$T6 - T5 \geq 0.2 \qquad T1 - T11 \geq 0.2$$
$$T4 - T6 \geq 0.2 \qquad T10 - T12 \geq 0.2$$

and 1.1 $\geq$ TDS $\geq$ 0.1

The Objective function which is to be minimized is

Min [T1×TDS1+T2×TDS2+T3×TDS3+T4×TDS4+T5×TDS5+T6×TDS6+T7×TDS7+T8×TDS8+T9×TDS9+T10×TDS10+T11×TDS11+T12×TDS12]

The relays which are used are Inverse Over-current relays have inverness in their characteristics.

Result of LP on IEEE9 Bus system

By using short-circuit and pick-up value in program optimal results are obtained.

Table 4.9: Primary/Back-up Relay operating time for IOC relay

Primary Relay No	TDS	Operating time(Sec.)	Back-up Relay No	TDS	Operating time(Sec)
1	0.2207	0.4355	3	0.3648	0.6355
2	0.3295	0.4653	12	0.1906	0.6652
3	0.3648	0.5392	5	0.2474	0.7392
4	0.2617	0.4726	2	0.3295	0.6724
5	0.2474	0.3515	7	0.3986	0.5514
6	0.3715	0.4903	4	0.2617	0.6903
7	0.3986	0.4882	9	0.6847	0.6882
8	0.2380	0.3380	6	0.3715	0.5380
9	0.3083	0.5381	11	0.3221	0.7382
10	0.3757	0.5328	8	0.2380	0.7329
11	0.3221	0.5059	1	0.2207	0.7059
12	0.1906	0.4160	10	0.3757	0.6161

On implementing linear programming method to have optimal selection of Time Dial

Setting for each relays are shown in table 4.9. The program gives us optimal value of TDS for each relay which intern gives primary and back-up relay coordinated.

Min [1.9733×TDS1+1.4123×TDS2+1.4782×TDS3+1.8059×TDS4+1.4210×TDS5 +1.3198×TDS6+1.2249×TDS7+1.4204×TDS8+1.7457×TDS9+1.4182×TDS10 +1.5709×TDS11+2.1827×TDS12]= 5.5738

The Optimization is terminated after 8 iterations.

Results obtained for IOC relay from LP

The results obtained in table 4.9 are for Inverse Over-current Relay. The same can be exercised for IDMT over-current relay where invernesses and definite time characteristics are required to be exploited. The results obtained are shown in table 4.10. Operating time of IDMT relay can be defined as

$$t_{op} = \frac{0.14}{[(\frac{I_f}{I_p})^{0.02} - 1]} \times TDS \tag{4.2}$$

Table 4.10: Primary/Back-up Relay operating time for IDMT relay

Primary Relay No.	TDS	Operating time(Sec)	Back-up Relay No.	TDS	Operating time(Sec)
1	0.1107	0.4445	3	0.1814	0.6445
2	0.1653	0.4781	12	0.1000	0.7049
3	0.1814	0.5486	5	0.1238	0.7484
4	0.1321	0.4861	2	0.1653	0.6860
5	0.1238	0.3603	7	0.1977	0.5605
6	0.1869	0.5060	4	0.1321	0.7060
7	0.1977	0.4977	9	0.1539	0.6977
8	0.1217	0.3540	6	0.1869	0.5541
9	0.1539	0.5478	11	0.1607	0.7477
10	0.1922	0.5583	8	0.1217	0.7580
11	0.1607	0.5158	1	0.1107	0.7158
12	0.1000	0.4434	10	0.1922	0.6435

Min [4.0155×TDS1+2.8929×TDS2+3.0248×TDS3+3.6804×TDS4+2.9104×TDS5 +2.7078×TDS6+2.5178×TDS7+2.9092×TDS8+3.5600×TDS9+2.9048×TDS10 +3.2102×TDS11+4.4344×TDS12]= 5.7415

The Optimization is terminated after 9 iterations.

Linear Programming can also be done for electromechanical relay with modification in coordination time interval which comprises of additional overshoot time. Due to mechanical inertia, disc or cup type electromechanical relay takes more time to actuate on given plug setting compare to numerical relay. Restriction on setting range of electromechanical relay is always there over numerical or microprocessor relay.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

- The objective function of operating times of the primary relays is optimized subject to keeping the operation of the back-up relays coordinated. Such coordination has been done using Linear programming interior point solver persisting high degree of simplicity and versatility. The proposed methodology has been carried out on IEEE9 bus system and test system with real time data and result enhances the coordination problem.

- Primal dual infeasible interior point algorithm approaches optimal coordination in-terms of TDS and operating time between primary and secondary relay pair without violating any bounding for IEEE9 bus system as well as test system with real time data. The proposed methodology satisfy the objective for different characteristics of relay without resulting in any miscoordination.

5.2 Future Scope

- The proposed methodology satisfy coordination problem for a close-in fault in transmission line for different characteristics of relay which can be enhanced by having a comparison between the operating times of the relays when a fault occurs in the middle of the line. An event of line outage and line contingencies can also be taken into consideration while implementing proposed method.

- Mixed Integer Programming (MIP) and Simplex Method can also be implement to enhance the optimal coordination with variation in number of iteration required. The proposed work can be extended for Linear programming with Active set strategy two-phase method to minimize the operating time of the relays for large or complex power system.

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Appendix A

Reference Data

A.1 Linprog function in MATLAB

In this relay coordination i have taken three bus system case to study coordination. This example is solved to understand relay coordination for simple three bus network. In this case, each protection zone corresponds with one of the transmission lines. The fault after the breaker will have the maximum fault current.

The linprog output structure is contains the constrviolation field, which reports the maximum constraint function at the final point. The interior-point algorithm of linprog solve different solutions and can solve more problems. In some cases, calling linprog with the lambda (Lagrange multipliers) output argument, with the options 'LargeScale' set to 'off' and 'Simplex' set to 'on'. Let us take one example, to get better information of it,

Finds the minimum of a problem specified by Min xf^Tx such that

$$A \times x \leq b,$$
$$A_{eq} \times x = b_{eq}$$
$$lb \leq x \leq ub$$

f, x, b, b_{eq}, lb, and ub are vectors, and A and A_{eq} are matrices.

x = linprog(f,A,b)

x = linprog(f,A,b,A_{eq},b_{eq})

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub)

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub,x0)

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub,x0,options)

x = linprog(problem)

$[x, fval]$ = linprog(...)

$[x, fval, exitflag]$ = linprog(...)

$[x, fval, exitflag, output]$ = linprog(...)

$[x, fval, exitflag, output, lambda]$ = linprog(...)

DESCRIPTION

Linprog solves linear programming problems.

x = linprog(f,A,b) solves min f×x such that A×x≤b.

x = linprog(f,A,b,A_{eq},b_{eq}) solves the problem above while additionally satisfying the equality constraints A_{eq}×x = b_{eq}. Set A = [] and b = [] if no inequalities exist.

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub) defines a set of lower and upper bounds on the design variables, x, so that the solution is always in the range lb . x . ub. Set A_{eq} = [] and b_{eq} = [] if no equalities exist.

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub,x0) sets the starting point to x0. This option is only available with the medium-scale algorithm (the LargeScale option is set to 'off' using optimset). The default large-scale algorithm and the simplex algorithm ignore any starting point.

x = linprog(f,A,b,A_{eq},b_{eq},lb,ub,x0,options) minimizes with the optimization options specified in the structure options. Use optimset to set these options.

x = linprog(problem) finds the minimum for problem, where problem is a structure described in Input Arguments.It create the structure problem by exporting a problem from Optimization Tool, as described in Exporting to the MATLAB Workspace.

$[x, fval]$ = linprog(...) returns the value of the objective function fun at the solution x: fval = f'×x.

$[x, fval, exitflag]$ = linprog(...) returns a value exitflag that describes the exit condition.

$[x, fval, exitflag, output]$ = linprog(...) returns a structure output that contains information about the optimization.

$[x, fval, exitflag, output, lambda]$ = linprog(...) returns a structure lambda whose fields contain the Lagrange multipliers at the solution x.

INPUT ARGUMENTS

Function Arguments contains general descriptions of arguments passed into linprog. Options provides the function-specific details for the options values.

Table A.1: Input argument description

f	Linear objective function vector f
A_{ineq}	Matrix for linear inequality constraints
b_{ineq}	Vector for linear inequality constraints
A_{eq}	Matrix for linear equality constraints
b_{eq}	Vector for linear equality constraints lb Vector of lower bound sub Vector of upper bounds
x0	Initial point for x, active set algorithm only
solver	'linprog'
Option s	Options structure created with optimset

OUTPUT ARGUMENTS

Function Arguments contains general descriptions of arguments returned by linprog. This section provides function-specific details for exitflag, lambda, and output.

Exitflag Integer identifying the reason the algorithm terminated. The following lists the values of exitflag and the corresponding reasons the algorithm terminated.

Table A.2: Output argument description

1	Function converged to a solution x.
0	Number of iterations exceeded options. MaxIter
-2	No feasible point was found.
-3	Problem is unbounded.
-4	None value was encountered during execution of the algorithm.
-5	Both primal and dual problems are infeasible.
-7	Search direction became too small. No further progress could be made.

Lambda Structure containing the Lagrange multipliers at the solution x (separated by constraint type). The fields of the structure are

- **lower :** Lower bounds lb
- **Upper :** Upper bounds ub
- **Inequlin :** Linear inequalities
- **Eqlin :** Linear equalities

Output Structure containing information about the optimization. The fields of the structure are

- **iterations:** Number of iterations
- **algorithm:** Optimization algorithm used
- **cgiterations:** 0(large-scale algorithm only, included for backward compatibility)
- **message:** Exit message

- **constrviolation:** Maximum of constraint functions
- **firstorderopt:** First-order optimality measure

A.2 IEEE9 Bus Data

Various parameters for IEEE9 Bus are as follows[12]

Table A.3: Transmission Line Data

From Bus	To Bus	Series Resistance in pu	Series Reactance in pu	Shunt Suceptance in pu
1	4	0.0000	0.0576	0.0000
4	6	0.0170	0.0920	0.1580
6	9	0.0390	0.1700	0.3580
9	3	0.0000	0.0586	0.0000
9	8	0.0119	0.1008	0.2090
8	7	0.0085	0.0720	0.1490
7	2	0.0000	0.0625	0.0000
7	5	0.0320	0.1610	0.3060
5	4	0.0100	0.0850	0.1760

Table A.4: Generator Data

Variable	Generator-1	Generator-2	Generator-3
X_d(pu)	0.1460	0.8958	1.3125
$X_d^{'}$(pu)	0.0608	0.1198	0.1813
$T_{do}^{'}$(pu)	8.96	6.0	5.89
X_q(pu)	0.0969	0.8645	1.2578
$X_q^{'}$(pu)	0.0608	0.1198	0.1813
$T_{qo}^{'}$(pu)	0.3100	0.5350	0.6000
H(sec)	23.46	6.4	3.01
D(pu)	0.0254	0.0066	0.0026

Table A.5: Transformer Data

Variable	Transformer-1	Transformer-2	Transformer-3
Primary(kV)	16.5	18	13.8
Secondary(kV)	220	220	220
MVA Rating	100	250	250
%Z	5.76	15.6	15062

Table A.6: Exciter Data

Variable	Exciter-1	Exciter-2	Exciter-3
K_A(pu)	25	25	25
T_A(pu)	0.2	0.2	0.2
K_E(pu)	1.0	1.0	1.0
T_E(pu)	0.314	0.314	0.314
K_F(pu)	0.0805	0.0805	0.0805
T_F(pu)	0.35	0.35	0.35

Table A.7: Bus Data

Bus No	Bus Type	Generation in pu P_G	Generation in pu P_Q	Load in pu P_L	Load in pu Q_L
1	Swing	-	-	0.0000	0.0000
2	PV	1.6300	-	0.0000	0.0000
3	PV	0.8500	-	0.0000	0.0000
4	PQ	0.0000	0.0000	0.0000	0.0000
5	PQ	0.0000	0.0000	1.2500	0.5000
6	PQ	0.0000	0.0000	0.9000	0.3000
7	PQ	0.0000	0.0000	0.0000	0.0000
8	PQ	0.0000	0.0000	1.0000	0.3500
9	PQ	0.0000	0.0000	0.0000	0.0000

Appendix B

Matlab Program

B.1 LP for IOC relay

```
Ip=[0.514,0.514,0.420,0.420,0.382,0.382,0.363,0.363,0.401,0.401,0.636,0.636]
If=[2.852,0,0,0,1.500,0;
0,5.460,0,2.700,0,0;
2.900,0,4.034,0,0,0;
0,0,0,2.716,0,1.530;
0,0,1.200,0,4.002,0;
0,3.836,0,0,0,4.750;
5.417,0,0,0,4.030,0;
0,3.796,0,1.100,0,0;
1.830,0,2.752,0,0,0;
0,0,0,4.209,0,3.101;
0,0,2.800,0,5.375,0;
0,1.700,0,0,0,3.009;]
for i=1:12
for k=1:6

p(i,k)=0.14/(((If(i,k)/Ip(i)))^0.04-1)
end
```

```
end
f=[ p(1,1),
p(2,2),
p(3,3),
p(4,4),
p(5,5),
p(6,6),
p(7,1),
p(8,2),
p(9,3),
p(10,4),
p(11,5),
p(12,6)];


A=[ p(1,1), 0, -p(3,1), 0, 0, 0, 0, 0, 0, 0, 0, 0;
0, P(2,2), 0, 0, 0, 0, 0, 0, 0, 0, 0, -p(12,2);
0, 0, P(3,3), 0, -p(5,3), 0, 0, 0, 0, 0, 0, 0;
0, -p(2,4), 0, P(4,4), 0, 0, 0, 0, 0, 0, 0, 0;
0, 0, 0, 0, P(5,5), 0, -p(7,5), 0, 0, 0, 0, 0;
0, 0, 0, -p(4,6), 0, P(6,6), 0, 0, 0, 0, 0, 0;
0, 0, 0, 0, 0, 0, p(7,1), 0, -p(9,1), 0, 0, 0;
0, 0, 0, 0, 0, -p(6,2), 0, p(8,2), 0, 0, 0, 0;
0, 0, 0, 0, 0, 0, 0, 0, p(9,3), 0, -p(11,3),0;
0, 0, 0, 0, 0, 0, 0, -p(8,4), 0, p(10,4), 0, 0;
-p(1,5), 0, 0, 0, 0, 0, 0, 0, 0, 0, p(11,5), 0;
0, 0, 0, 0, 0, 0, 0, 0, 0, -p(10,6), 0,p(12,6) ;]

b= -[0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;]
```

```
lb=[0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1]
ub=[1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1]

[x,fval,exitflag,output] = linprog(f,A,b,[],[],lb,ub)
```

B.2 LP for IDMT Relay

```
Ip=[0.514,0.514,0.420,0.420,0.382,0.382,0.363,0.363,0.401,0.401,0.636,0.636]
If=[2.852,0,0,0,1.500,0;
0,5.460,0,2.700,0,0;
2.900,0,4.034,0,0,0;
0,0,0,2.716,0,1.530;
0,0,1.200,0,4.002,0;
0,3.836,0,0,0,4.750;
5.417,0,0,0,4.030,0;
0,3.796,0,1.100,0,0;
1.830,0,2.752,0,0,0;
0,0,0,4.209,0,3.101;
0,0,2.800,0,5.375,0;
0,1.700,0,0,0,3.009;]
for i=1:12
for k=1:6

p(i,k)=0.14/(((If(i,k)/Ip(i)))^0.02-1)
end


end
f=[ p(1,1),
p(2,2),
```

```
p(3,3),
p(4,4),
p(5,5),
p(6,6),
p(7,1),
p(8,2),
p(9,3),
p(10,4),
p(11,5),
p(12,6)];


A=[ p(1,1), 0, -p(3,1), 0, 0, 0, 0, 0, 0, 0, 0, 0;
0, P(2,2), 0, 0, 0, 0, 0, 0, 0, 0, 0, -p(12,2);
0, 0, P(3,3), 0, -p(5,3), 0, 0, 0, 0, 0, 0, 0;
0, -p(2,4), 0, P(4,4), 0, 0, 0, 0, 0, 0, 0, 0;
0, 0, 0, 0, P(5,5), 0, -p(7,5), 0, 0, 0, 0, 0;
0, 0, 0, -p(4,6), 0, P(6,6), 0, 0, 0, 0, 0, 0;
0, 0, 0, 0, 0, 0, p(7,1), 0, -p(9,1), 0, 0, 0;
0, 0, 0, 0, 0, -p(6,2), 0, p(8,2), 0, 0, 0, 0;
0, 0, 0, 0, 0, 0, 0, 0, p(9,3), 0, -p(11,3),0;
0, 0, 0, 0, 0, 0, 0, -p(8,4), 0, p(10,4), 0, 0;
-p(1,5), 0, 0, 0, 0, 0, 0, 0, 0, 0, p(11,5), 0;
0, 0, 0, 0, 0, 0, 0, 0, 0, -p(10,6), 0,p(12,6) ;]

b= -[0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;0.20;]


lb=[0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1;0.1]
ub=[1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1;1.1]
```

$[x, fval, exitflag, output]$ = linprog(f,A,b,[],[],lb,ub)