SYMPATHETIC TRIPPING OF DIRECTIONAL OVERCURRENT RELAYS IN POWER NETWORK

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 **SYMPATHETIC TRIPPING OF DIRECTIONAL OVERCURRENT RELAYS IN POWER NETWORK** in the 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**, submitted in the **Department of Electrical Engineering**, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from May 2006 to June 2007 under the supervision of **Dr. H. O. Gupta**, Professor, Electrical Engineering Department, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(ROHITH KUMAR.H.C)

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

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ABSTRACT

Protective relaying plays a vital role in optimum operation of electric power system. The relays detect the abnormal system conditions and act in a predetermined fashion to disengage the troubled area while continuing to serve the rest of the system. Ideally, the primary relays have to initiate the corrective action, but in some cases it may fail to operate, thus suitable backup protection scheme is also necessary. Therefore, the problem of relay coordination is to determine the sequence of relay operations for each conceivable abnormal condition, and isolate the faulted area, with sufficient coordination margins in minimum time.

Normally, transmission lines are protected using overcurrent, distance, or pilot-relaying schemes depending on the requirement. However, lately, directional overcurrent relays (DOCRs) are being widely accepted and used for protecting radial, ring sub-transmission and distribution systems. The key reasons for such transformation by the utilities are that, DOCRs offer a good technical and economical alternative for protection.

Coordinating the operation of DOCRs, in large interconnected power networks with multiple loops and sources poses serious trouble. Literature reveals that protection engineers are striving hard to achieve the required levels of system reliability. However, this is tough to achieve, because, anticipating each abnormal condition and providing protection to it is just not workable. Interestingly, during early days, the coordination was performed through laborious and tiresome hand calculations. But the advent of computers, has relived engineers from this painstaking task. Now, the research is oriented towards developing better, faster, reliable and adaptive solution strategies to ensure improved levels of reliability.

Most of the approaches available in the literature are based upon coordination philosophy or on optimizing the relay settings. The coordination philosophy based approaches need elaborate and complicated topological analysis programs, yet the solution is not optimal in any strict sense. In contrast, parameter optimization methods are simple and easy to handle. In these techniques, a performance function is formulated and minimized subject to certain coordination criteria. The coordination criteria actually implement the coordination rules in the form of constraints. The performance function chosen must reflect the desired operation of DOCRs. Desired

operation means that relays must act selectively to give protection to every portion of the power system.

The present dissertation work, compiles the most of the significant contributions made to optimally coordinate DOCRs in large power network. Various drawbacks of the existing techniques are discussed, two new approaches are proposed to overcome these deficiencies. The proposed approaches use a global optimization technique, and optimization if performed in a non-linear environment. The applicability of the proposed approaches is demonstrated on sample 6-bus, IEEE 14-bus and IEEE 30-bus systems. Performance evaluation of proposed approaches is also presented.

Although, optimal settings were obtained using global optimization technique, investigations revealed that larger power systems (like IEEE 30-bus system) were still subjected to risk of sympathy trips. Sympathy trips are of serious concern to operators and planners, since they introduce multiple contingencies, and affect the system optimum operation. Current thesis work suitably addresses the problem of sympathetic tripping of DOCRs in large interconnected power systems by proposing two approaches. The results suggest that both the proposed approaches were successful in tackling sympathy trips and ensuring a reliable power supply.

with Mr. V.S.Sriram and Mr. Sheri Sundeep and this writing space is not enough to write about the memories I have in my mind.

I am thankful to the technical staff of the SEOR Lab Shri Kalyan Singh, Shri C.M. Joshi, and other staff members for their timely cooperation and needful help.

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My heartiest gratitude goes to my parents, brothers, sister and other members of family, for constantly supporting, which allowed me to concentrate on my work.

I would like to dedicate this research work to my family.

Acknowledge Him in all Thy ways and He shall direct Thy paths.

(Rohith Kumar .H.C)

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LIST OF SYMBOLS

A_m	Set of backup relays corresponding to near-end fault near m^{th} primary relay
B_n	Set of backup relays corresponding to n^{th} primary relay for a far-end fault
CT_{pri}	Current transformer primary current rating
$f(PS_i)$	Function of plug setting of i^{th} relay
F_g	Amplification/scaling factor in g^{th} generation
F_U, F_L	Upper and lower limit of scaling factor respectively
g	Current generation number
Ge_{MAX}	Maximum number of generations
I_{Fault}	Fault current measured near relay
I_{nor}	Normal line current
I_{pck}	Relay pickup current setting
N	Total no. of relays responding to near-end and far-end faults (N_{nr}+N_{fr})
N_{fr}	Total no. of relays responding to far-end faults
N_{nr}	Total no. of relays responding to near-end faults
N_R	Total no. of relays in the system
OLF	Over load factor
OT_{bck}	Operating time of backup relay
OT_{fr_j}	Operating time of j^{th} primary relay for far-end fault
OT^k	Operating time of k^{th} relay
OT^l	Operating time of l^{th} relay
OT_{LP_i}	Operating time of i^{th} primary relay under linear formulation
OT_{nr_i}	Operating time of i^{th} primary relay for near-end fault
OT_{pri}	Operating time of primary relay
${}_{tr}OT^k$	Operating time of k^{th} relay under transient condition
${}_{tr}OT^l$	Operating time of l^{th} relay under transient condition
$OT^m_{pri\_nr}$	Operating time m^{th} primary relay for a near-end fault
$OT^{m_i}_{pri\_nr}$	Operating time of i^{th} backup of m^{th} primary relay for a near-end fault

${}_{tr}OT^{m}_{pri\_nr}$	Operating time of m^{th} primary relay for a near-end fault under transient condition
${}_{tr}OT^{m_i}_{bck\_nr}$	Operating time of i^{th} backup of m^{th} primary relay for a near-end fault under transient condition
$OT^{n}_{pri\_fr}$	Operating time of n^{th} primary relay for a far-end fault
$OT^{n_j}_{pri\_fr}$	Operating time of j^{th} backup for n^{th} primary relay for a far-end fault
${}_{tr}OT^{n}_{pri\_fr}$	Operating time of n^{th} primary relay for a far-end fault under transient condition
${}_{tr}OT^{n_j}_{bck\_fr}$	Operating time of j^{th} backup for n^{th} primary relay for a far-end fault under transient condition
PS^{k}_{max}	Maximum PS of k^{th} relay
PS^{k}_{min}	Minimum PS of k^{th} relay
TDS^{k}_{max}	Maximum TDS of k^{th} relay
TDS^{k}_{min}	Minimum TDS of k^{th} relay
X_{best_g}	Best decision vector up to 'g'

LIST OF ABBREVATIONS

ADE	Adaptive Differential Evolution
Bck/Pri	Backup/ Primary
CT	Current Transformer
CTI	Coordination Time Interval
CTR	Current Transformer Ratio
DE	Differential Evolution
DOCR	Directional Overcurrent Relay
FACTS	Flexible AC Transmission System
GA	Genetic Algorithm
GAMS	General Algebraic Modeling System
LLOT	Lower Limit of Primary Operating Time
LPP	Linear Programming Problem
MINLP	Mixed Integer Non-Linear Programming
MIP	Mixed Integer Programming
NADE	Non Adaptive Differential Evolution
NLP	Non-linear Programming
OLF	Over Load Factor
PS	Plug Setting
PSM	Plug Setting Multiplier (Multiple of Tap Current Setting), i.e., (I/I_{pck})
PSO	Particle Swarm Optimization
RST	Random Search Technique
SQP	Sequential Quadratic Programming
TDS	Time Dial, or Time Multiplier, Setting
ULOT	Upper Limit of Primary Operating Time

CHAPTER - 1

INTRODUCTION

1.1 GENERAL

An increase in the dependability on electricity, in the recent times has elevated the need for achieving the acceptable level of reliability, quality and safety of electric supply at affordable prices [1]. Also, the deregulation of the electricity market has forced the utilities to focus towards meeting these performance goals competitively. Already, several countries have introduced heavy penalties if the utility fails to meet the consumer's demand. As a result, the users are continuously demanding reliable and quality power supply with shorter interruption durations and restoration times.

The modern electric power system is highly interconnected, and comprises of several complex loops and multiple sources. Even with this complexity, it can be broadly sub-divided into:

- Generation
- Transmission
- Distribution

Each of the above classifications involves various equipments which ensure a consistent operation of the system. Among these equipments, the most critical components are the protective relays, which are installed to detect the abnormal power system conditions and initiate suitable corrective measures to prevent power apparatus from being damaged [1]-[3]. This is illustrated using a three-layered structure given by Fig.1.1. At the bottom of the level is the power equipment which needs to be protected (generator, transformer, transmission line etc). The next layer consists of control equipments, these help in maintaining the power system at normal voltage and frequency level. Control layer may have a hierarchy of its own, consisting of different local and centralized control functions. And finally, the protection equipments, these are the faster operating devices designed to protect power apparatus. The operation of protection equipments usually changes the structure of the power system. Therefore, it is necessary to coordinate their operation and minimize the damage of system elements [2].

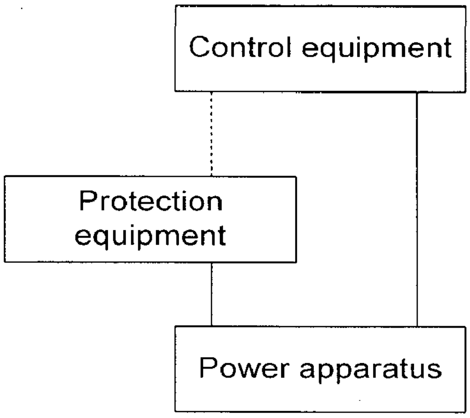

Fig.1.1: Simplified three layered structure of power system

1.2 PROTECTION REQUIREMENTS

The key function of any protective relaying is to promptly remove that equipment from service which is misbehaving [2]. However, relays are mostly operated in an interconnected power system, and their operation needs to take into account certain inherent qualities as mention below [3].

- Reliability: It is the degree of certainty with which given equipment performs its desired function. As far as relays are concerned, reliability has two-pronged components:
  - Dependability- The surety of operation of relay on the occurrence of fault.
  - Security- The ability of protective system to avoid mal-operation of relays.
- Speed: To clear the fault in minimum time and avoid any further damage of power equipment.
- Selectivity: Disengaging only the faulted section of network while maintaining continuity in healthy sections.
- Simplicity: The protective relay system needs to be simple and straightforward while still accomplishing the intended performance goals.
- Economical: maximum protection at minimum cost.

In real-life situations, satisfying all the above requirements simultaneously is a tough task, and protection engineers end up choosing a compromised optimum protection strategy.

1.3 PROTECTION PHILOSOPHY

The general approach for the use of relays is to sub-divide the power system into separate zones (i.e. protection zones), each of which can be individually protected and disconnected during abnormalities. Noticeably, all the power system elements must be encompassed within at least one zone [2]. These protection zones overlap each other, thus, if a fault occurs in these areas, then more than one relay will operate. The different protection zones are illustrated in Fig. 1.2 and they fall in any one of the categories mentioned below [3].

- Generators and generator-transformer units
- Transformers
- Buses
- Transmission lines
- Utilization equipments (i.e. motors or static loads)

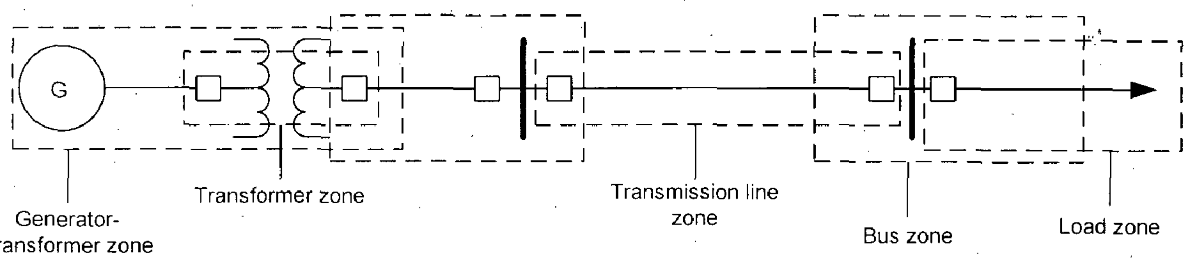

Fig 1.2: Typical power system with primary protection zones

It is essential that any faults should be isolated even if the primary protection system fails to operate. Therefore, every power system element has to be protected with both primary and back-up relays. The primary relays are the first to operate on detection of a fault. In case of failure of operation of primary relays, the back-up relay operates and isolates the fault. Any given equipment may have more than one back-up relay. Hence, it is not uncommon to find a relay acting as primary for some equipment, and as back-up for some other device.

1.4 RELAY COORDINATION

If more than two protective devices are installed in series, and they operate in a predefined sequence, then they are said to be coordinated or selective [4], [5]. Nonetheless, the problem of relay coordination is to determine the sequence of operation of relays for each faulted section and guarantee timely isolation of faulted section of network with sufficient coordination margins [6]. Or simply, relay coordination is a process of identifying the suitable back-up/primary (*Bck/Pri*) pairs and making sure that they operate in a predefined manner. However, identification of this sequence is truly a function of power network topology, relay characteristics and protection philosophy.

As per the coordination philosophy, to ascertain that primary relay gets sufficient chance to clear fault occurring in its protective zone, certain definite time interval has to be maintained between the operating times of primary relay and its corresponding back-up. This definite minimum time delay is known as coordination time interval (*CTI*) or coordination margin [3].

The coordination of protective relays is an important aspect of protection system design. A detailed survey of the literature reveals that achieving a foolproof protective system is nearly impossible [5]-[7]. Therefore two approaches are normally accepted during coordinating protective devices: non-optimal and optimal [8]-[10]. Relaying schemes and settings vary with the utility, and are highly dependent on the coordination philosophy adopted and practiced by the respective utility. Usually, most of the crucial and worst case scenario's of network are considered during the coordination. Even then the protection engineer must be ready to accept a few failures, mainly due to the large set of possible network configurations or wrong relay settings. Probably looking into the various difficulties encountered during coordination, *G.D. Rockefeller et al.* [11] have expressed that:

"It is not usually feasible to achieve coordination for every conceivable permutation of power system configuration. A key aspect of settings is the choice of contingencies for which coordination is attempted. Accordingly, the engineer must choose what he considers are those contingencies with reasonable probabilities of being encountered. Even then he usually must make compromises, accepting some mis-coordination or slim timing for some contingencies. In addition, to some extent the quality of protection for normal conditions is degraded by the need to cover contingencies".

1.5 OBJECTIVES OF THE THESIS

The key objectives of this research includes a comprehensive study of optimal coordination problem of directional overcurrent relays (*DOCRs*), identification of deficiencies in already existing methodologies, and suitably develop appropriate schemes to overcome most of these deficits. The following is the point-wise summary of author's contribution in the aimed area of research:

1. Initially, a critical literature survey was conducted on optimal coordination problem of DOCRs; a brief overview of this survey has also been presented here. Various intricacies associated with relay coordination were looked into, and a detailed insight of various types of problem formulation, assumptions and solution techniques employed for optimal coordination were analyzed. Also, a brief compilation of these studies have been presented to understand and appreciate the problem complexity.
2. A new approach to solve relay coordination problem using evolutionary technique has been proposed. The novel evolutionary technique being used here is known as differential evolution (*DE*) and of late has proven its capability in obtaining global optimum solution for a variety of real-life situations. However, applicability of DE has not been tested much on power system problems. Therefore, an effort has been made to evaluate DE effectiveness in solving relay coordination problem. The comparison of results obtained from conventional optimization technique against evolutionary technique has also been furnished. The proposed approach gave superior results and was able to resolve solution infeasibility problem faced with usage of conventional optimization technique.
3. A clear investigation into sympathy tripping of relays in power network was carried out. The reasons for such nuisance trippings, and their consequences were studied in detail. Noticeable efforts already existing in this research area have also been presented and a few possible solution strategies are discussed.
4. Among the several possible alternative approaches to resolve sympathetic tripping problem, an attempt has been made to obtain solution through two phase approach. Effectiveness and the simplicity of this proposed approach has also been elaborated.

1.6 ORGANIZATION OF THE THESIS

The organization and important developments of this thesis are given chapter by chapter in the following sequence:

Chapter 2 presents an overview of optimal relay coordination issues in an interconnected power network, which includes various details such as problem formulations, assumptions and solution techniques being used so far.

In chapter 3, the various aspects of applicability and requirement of usage of DE are presented. Also, the kind of DE used during current research work and its computational flow is briefed.

Chapter 4 presents approaches for optimal relay coordination of DOCRs. Two alternative approaches for implementation of the scheme are investigated. The effectiveness of proposed approaches against conventional optimization based approach are highlighted and discussed.

Chapter 5 offers a clear insight into sympathetic tripping problem of DOCRs occurring in power networks.

In chapter 6, two approaches have been proposed to resolve the issue of sympathetic tripping of DOCRs. The implementation of proposed approaches and the results obtained are discussed.

Chapter 7 gives findings and scope of future research in the area of relay coordination.

CHAPTER - 2

OPTIMAL RELAY COORDINATION

2.1 INTRODUCTION

Modern day power transmission systems are vastly interconnected and involve multiple sources and complex loops. Depending on the need, transmission lines of such vast networks may be protected through overcurrent, distance or pilot-relaying equipment [6]. Incidentally, directional overcurrent relays (DOCRs) appear to offer a good technical and economical choice, and hence are widely preferred for primary protection of lines at sub-transmission level, and also for secondary protection at transmission levels [5]-[7]. However, coordinating the operation of all such relays is a time-consuming and laborious task. Interestingly, during early days, coordination was carried out manually and often involved extensive calculations with very little assurance of quality of protection [12]-[15]. Moreover, initially researchers used elaborate and complex topological analysis programs to determine the break point set, relative sequence matrix, selection pairs etc. Soon these methods became unpopular due to large computation time and efforts involved, and for the same reasons settings once obtained were not revised quiet frequently and this jeopardized the power system security. However, recently a great deal of noticeable efforts have been made to automate the coordination process, and several offline and online approaches have been suggested [7], [11]-[14]. Better coordination is made possible these days through improved user and computer interaction.

An insight into literature reveals that entire relay coordination approaches can be categorized broadly into two types. The first one is based on traditional coordination philosophy and other on optimization of settings [7], [13]. Coordination by conventional philosophy is achieved only for a predetermined set of abnormal conditions and system contingencies. Hence, addition of any new condition, the technique would be unable to determine relay response. Conversely, coordination by optimization techniques is gaining momentum over conventional techniques owing to their inherent advantages listed below.

- Elimination of need to determine break set points

- Simplicity of technique
- Assurance of better quality of protection
- Flexibility of implementation and modification of coordination program

The optimal relay coordination by using optimization of parameters is briefly discussed in the following section.

2.2 OPTIMIZATION THEORY BASED RELAY COORDINATION

In this coordination philosophy, a performance function is chosen and its parameters are optimized subjected to certain criteria. These criteria are simply the coordination rules, and they act as constraints during optimization. The performance function chosen for optimizing would reflect the desired operation of relays. The desired operation refers to selecting suitable relay settings such that fundamental protective functions are met under the requirement of selectivity, sensitivity, reliability and speed [8], [15]. All these requirements need to be fulfilled under variety of system conditions and configurations. Therefore, various critical and worst cases for a given power network should be considered during optimization [8], [9]. Inclusion of future modifications and dynamic changes occurring in power system would further improve the quality of protection [8], [16], [17].

In previous works, coordination problem has been formulated either as a linear, nonlinear or mixed integer nonlinear programming problem depending on the type of variables [7], [18]. Each DOCR has two settings to be optimized: time dial setting (TDS) and pickup current setting (I_{pck}) and the type of coordination formulation is decided by I_{pck}. If I_{pck} is set fixed, then the problem becomes a linear programming problem (LPP), and if it is treated as continuous, then formulation is nonlinear programming (NLP) problem. Finally, if discrete values of I_{pck} are considered, the problem becomes a mixed integer nonlinear programming (MINLP) problem [18]. The solution to LPP formulation has been obtained using techniques like simplex, two-phase simplex and dual-simplex [8], [16], [18], [19]. Whereas, the nonlinear programming techniques such as sequential quadratic programming (*SQP*), Rosenbrock-hill climb method, generalized reduced gradient technique etc were used to solve the NLP [6], [8], [12]. In [22], optimization based on constraints only was proposed and optimum relay operating times were obtained by setting TDS at minimum and gradually increasing their values.

Researchers have also suggested network decomposition approaches to achieve faster coordination mainly for large power networks [8], [21]. Here, the entire power system is decomposed into a number of convenient subnetworks called blocks, by identifying boundary buses, branches and relays. *Urdaneta et al* [16] suggested considering transient network configurations during optimization, but handling such large formulation may lead to obtaining suboptimal results. Consequently, references [23], [24] have proposed subsystem based approaches for optimal coordination in the event of structural or load changes. In [23], an automatic window identification and coordination technique was proposed to eliminate system-wide coordination. Whereas [24] suggested a scheme to identify local disturbed region around the place of disturbance and recoordinate only the relays in this region. Recently, stochastic optimization techniques like genetic algorithm (GA), random search technique (RST), particle swarm optimization (PSO) etc are also proposed for obtaining a global optimum for relay coordination problem [15], [25]-[29]. An overview of problem formulations utilized in optimal coordination of DOCRs is presented in subsequent section.

2.3 DOCR COORDINATION PROBLEM FORMULATION

The DOCRs are mainly used for protecting ring or meshed type systems, and systems with number of infeed points. The key reason for using DOCRs is that, the bi-directional overcurrent protection could produce unnecessary tripping of circuits [1]. Basically, DOCRs comprises of an overcurrent unit along with a power flow direction sensing unit. The DOCR operates if the sensed fault current is greater than a threshold value in a specified direction. They are placed at both ends of transmission line, and provide both primary and backup protection. Two settings associated with each DOCR are:

- Time dial setting (TDS)
- Plug setting (PS)

The TDS is defined as, the definite time delay before operation of a relay after sensing the fault (i.e. $I_{Fault}>I_{pck}$). Tap settings or PS are defined as multiples of I_{pck}, where I_{pck} is the minimum current for which the relay operates. In the case of phase relays, I_{pck} is taken after accommodating a small margin for overload above normal current as in (2.1).

$$I_{pck} = OLF * I_{nor} \tag{2.1}$$

The value of OLF depends on the system element being protected, and some typical values for certain power network elements are given in Table.2.1. During coordination, load transfer in both directions is considered to avoid the possible relay mal-operation owing to wrong polarization of directional unit, especially under heavy load transfer conditions [1], [5], [6].

Table.2.1: Typical values of overload factors

Power system element	OLF
Motors	1.05
Transmission lines	1.25-1.50
Distribution lines (under emergency)	2.0
Transformers and generators	1.25-1.50

The plug setting multiplier (PSM), is defined as the ratio of fault current to relay pickup or plug setting, and is evaluated using (2.2).

$$PSM = \frac{I_{Fault}}{PS * CT_{pri}} \tag{2.2}$$

Given the values of PS and TDS of a relay, its operating time can be calculated. The operating time (OT) of DOCR is a non-linear function of relay settings and current seen by the relay:

$$OT = f(I_{pck}, I) * TDS \tag{2.3}$$

The above equation is generally characterized as inverse characteristic curves of concerned relays for different values of the TDS. The mathematical definition of operating time as per IEC and IEEE standard is given by:

$$OT = \frac{\alpha * TDS}{PSM^{\beta} - 1.0} + \gamma \tag{2.4}$$

Constants α, β and γ signify the relay characteristic selected, their typical values are given in Table.2.2 [1], [5].

Table.2.2: Standard overcurrent relay constants as per IEEE and IEC

Characteristic curve	Standard	α	β	γ
Moderately inverse	IEEE	0.0515	0.02	0.114
Very inverse	IEEE	19.61	2.0	0.491
Extremely inverse	IEEE	28.2	2.0	0.1217
Standard inverse	IEC	0.14	0.02	0.0
Very inverse	IEC	13.50	1.0	0.0
Extremely inverse	IEC	80.00	2.0	0.0

2.3.1 Objective function

The key objective of optimal relay coordination is to minimize the total operating time for different abnormal conditions. Literature reveals variety of objective functions being utilized for optimization. However, near-end far-end based approach is good enough, as it considers most of the system conditions. In this approach, a fault is simulated on line near each relay and this in turn behaves as far-end fault for the relay on the other end of the line. For e.g. consider a fault F near relay R_{pri_nr} given in Fig.2.1, it is a near-end of this relay but the same is a far-end for R_{pri_fr}.

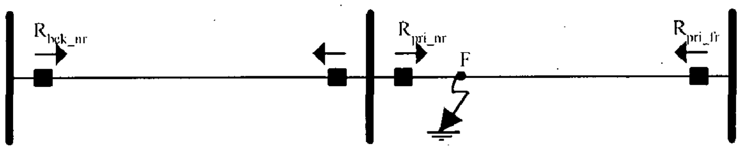

Fig.2.1: Diagram showing near-end and far-end fault for F

The near-end fault level is used to coordinate for high fault current, whereas the far-end fault level coordinates for low fault current [5], [6]. Therefore, conventionally the objective function for DOCR coordination (OBJ_{nr_fr}) is constituted as summation of primary operating times of relays responding to near-end and far-end faults as given in (2.5).

$$Minimize: \ OBJ_{nr\_fr} = \sum_{i=1}^{N_{nr}} OT_{nr\_i} + \sum_{j=1}^{N_{fr}} OT_{fr\_j} \tag{2.5}$$

If relays are to be coordinated only for the near-end fault level then, the objective to be optimized gets simplified to (2.6):

$$Minimize: \ OBJ_{nr} = \sum_{i=1}^{N_{nr}} OT_{nr\_i} \tag{2.6}$$

Although using near-end fault approach gives better objective value, the quality of coordination is sacrificed as few of the far-end constraints are violated. While coordinating in large power networks with high fault currents, a LPP formulation itself approximates the non-linearity sufficiently [22]. Such linear formulation is possible if PS is fixed, and it can be expressed as:

$$Minimize: \ OBJ_{LP} = \sum_{i=1}^{N} OT_{LP\_i} \tag{2.7}$$

2.3.2 Constraints

All the objective functions (2.5)-(2.7) mentioned above are subject to constraints, such as: coordination/selectivity constraints, bounds on relay settings and limits on operating times. These constraints are explained briefly in this section.

i. *Selectivity constraints*: A discrimination margin (Coordination time interval-CTI) is used between two successive relay characteristics, this is to avoid loss of selectivity due to one or more reasons mentioned below:
   - Breaker operating time
   - Relay overrun time after the fault has been cleared
   - Variations in fault levels
   - Errors in current transformers
   - Deviation from characteristic curves

The typical value used for CTI is between 0.20-0.40 secs, lower end is used during coordination in small networks while higher CTI is preferred for large networks. This discrimination in general is expressed as:

$$OT_{bck} - OT_{pri} \geq CTI \tag{2.8}$$

Each such constraint is subdivided into two type of constraint as under:

a. *Near-end selectivity constraints*: These constraints comprise of operating time of each primary relay sensing a near-end fault with its all corresponding backup relays, as in:

$$OT^{m_i}_{bck\_nr} - OT^{m}_{pri\_nr} \geq CTI \qquad i \in A_m \tag{2.9.a}$$

b. *Far-end selectivity constraints:* These constraints comprise of operating time of each primary relay sensing a far-end fault with its all corresponding backup relays, can be given as:

$$OT^{nj}_{bck\_fr} - OT^{n}_{pri\_fr} \geq CTI \qquad j \in B_n \tag{2.9.b}$$

ii. *Bounds on relay settings*: The TDS and PS of each DOCR is bounded by maximum and minimum limits given as under:

$$TDS^{k}_{min} \geq TDS^{k} \geq TDS^{k}_{max} \qquad \forall\, k = 1, 2, \ldots, N_R \tag{2.10.a}$$

$$PS^{k}_{min} \geq PS^{k} \geq PS^{k}_{max} \tag{2.10.b}$$

iii. *Limits on operating time of primary relays*: The protection should be accomplished within a stipulated upper limit (*ULOT*), and also not earlier than lower limit (*LLOT*).

2.4 REQUIREMENTS OF OPTIMAL RELAY COORDINTION PROBLEM

The generic requirements of an optimal relay coordination problem are mentioned in this section. The computational flow of proposed relay coordination procedure is also presented in Fig.2.2 [6].

1. Power network topology storage and retrieval scheme to facilitate simpler and faster accessibility of data during coordination process.
2. Load flow and fault analysis subroutines.
3. Algorithm for forming *Bck/Pri* relay pairs corresponding to each relay.
4. Algorithm for constituting objective function.
5. Algorithm for preparing selectivity constraints.
6. Optimization procedure to determine the optimal relay settings.

In the present work, fault analysis subroutine is implemented using Z_{BUS} building algorithm as per [30], [31]. The procedures required for determining the relay pairs, constituting objective function and selectivity constraints is similar to as in [6]. Optimal relay settings are computed using an evolutionary optimization technique called differential evolution (DE), and this technique is explained in the subsequent chapter.

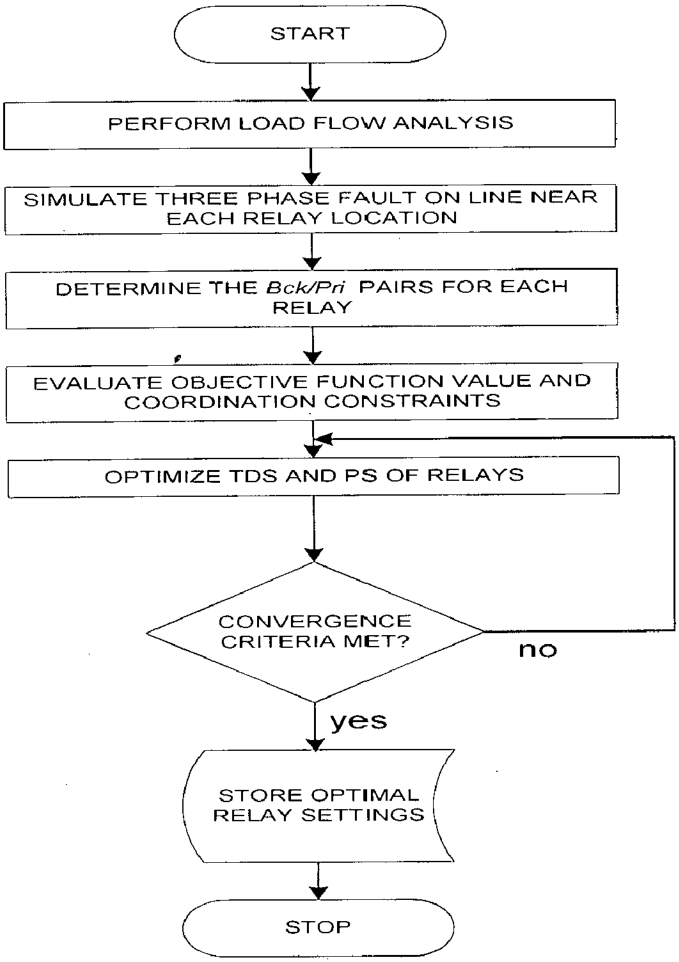

Fig.2.2: Flow chart for relay coordination

2.5 CONCLUSION

The DOCRs are the economical means of protecting the power networks. If such relays are placed in vast power networks, then coordinating their sequence of operation becomes a tedious job. Therefore, protection engineers depend on several computerized algorithms to obtain their optimal settings. In this view, an overview of necessity for coordinating relays, different problem formulations, techniques used for obtaining optimal settings and minimum requirements of an optimal coordination procedure was presented in this chapter.

The proper choice of optimization procedure plays a critical role in obtaining good solution. As observed from literature, several conventional and artificial intelligence based techniques are used. Most of these techniques suffer from one or another drawback. Hence, there is need for a robust optimizing algorithm to overcome these shortfalls, next chapter elaborates the shortfalls of existing techniques, and proposes a new technique.

CHAPTER - 3

DIFFERENTIAL EVOLUTION

3.1 INTRODUCTION

In many engineering design, managerial and many other day today real-life problems one is required to make tradeoffs between various factors to achieve a desirable outcome. Such an act of obtaining the best result under given circumstances is known as optimization [32], [33]. The availability of high speed computers at affordable price has increased the popularity of optimization techniques [34]. The ultimate aim of any optimization procedure would be choose the design/decision variables such that final goal is either minimized or maximized. For example, minimizing the overall weight of an aircraft, minimizing the communication time between two nodes, determining an optimal trajectory of a robot arm, designing buildings or dams for maximum safety etc. Therefore, it is clear that most of the real-life optimization problems are complex, and finding an optimal solution by examining every point in search space within acceptable time becomes impossible [33].

The optimum seeking methods can be classified into two: deterministic search techniques and stochastic optimization techniques. Deterministic search techniques are transitional rule based optimization approaches, and require certain auxiliary information such as gradient or search direction to proceed with their search. Moreover, few of these search techniques work with an assumption that function being optimized is unimodal and continuous [34]. Therefore, deterministic search techniques have limited applicability if a complex, real-life problem is considered [33]. Conversely, stochastic optimization techniques are well suitable for practical optimization problems which are characterized by mixed-continuous-discrete variables and discontinuous in a nonconvex design space [32]-[35]. These techniques are robust, relatively insensitive to noisy and/or missing data problems, simpler in implementation and obtain good solution at faster rate. Stochastic optimization techniques fall into two broad classes: local search and population-based searches. A brief insight into population-based search algorithms is presented in the following sub-section.

3.1.1 Population-based search techniques

In population-based search, the idea is to replace a single candidate solution (as in deterministic techniques) with a population of possible candidate solutions [33]. Initially, a random population is considered, and certain operations are performed on them to produce new candidates. The presence of population brings in other possibilities like, usage of two or more candidate solutions to obtain new solution and selecting candidates for next iteration. Few examples of population-based searches are: genetic algorithm, particle swarm optimization (PSO), simulated annealing, differential evolution etc. Figure 3.1 illustrates the population-based search techniques.

1.Begin: Initialize, Evlaute P(0), set t=1;
2.Select: Select P(t) from P(t-1);
3.Generate: Generate new candidate solution $P^{'}(t)$ through genetic operators;
4.Evaluate: Evaluate $P^{'}(t)$ and replace P(t) with $P^{'}(t)$;
5.Continue: Return to 2 untill convergence;

Fig.3.1: Population-based optimization algorithm

In literature, several kinds of population-based algorithms are popular, and among them the most commonly known is genetic algorithm (GA). These algorithms are based on mechanics of natural genetics and selection [34]. Since their introduction in 1975, several variants of this algorithm are already available. However, in the recent times, a new robust, fast converging global optimization technique known as differential evolution (DE) has come into existence [35]. DE has been tested on several numerical bench problems and found to be effective, and it seems to outperform many other population-based search algorithms including PSO [36], [37]. The next few sections describe DE and its operators.

3.2 DIFFERENTIAL EVOLUTION ALGORITHM

Differential evolution (DE) is a simple yet robust evolutionary technique seeking global optima in feasible search domain [36]. Initially, when it was introduced by Storn and Price in 1995, it was only meant to search the optimum in a continuous search area [38]. However, in recent times, the DE algorithm has gained popularity owing to its ease of handling, and excellent convergence properties. In DE, there are very few control parameters which need to be tuned [39]. The DE entirely corresponds to a typical evolutionary algorithm and above all it is close to GA. However, the main difference between GA and DE is the mutation scheme that makes DE self adaptive, and also the selection process [35], [40]. In DE, all solutions have same probability of being selected without depending on their performance (or fitness) value. The DE employs a greedy selection scheme, in which the better among the parent and offspring wins the competition [35], this arrangement speeds up the convergence. Nevertheless, most of the applications discussed in the literature are for solving continuous problems, and it is usual practice to solve discrete and integer problems as continuous and round off results to nearest available values. Lately, DE appears as one of the promising algorithm which handles discrete and integer design variables elegantly with very little modification in the algorithm [41], [42]. The DE algorithm takes three input parameters, i.e. population size NP, amplification/scaling factor F_g, and crossover probability P_{CR}. Most general computational flow of DE algorithm is demonstrated in Figure 3.2.

```
Input : NP, Ge_MAX, F_g, P_CR;
Initialization : random population P̂_0;
set i = 1;
While ( i ≤ Ge_MAX )
  Repeat : P̂_old = P̂_i-1;
       Mutation ( P̂_i-1 ) ;
       Crossover ( P̂_i-1 ) ;
       Select ( P̂_i-1 ) ;
       i + +;
end while
```

Fig.3.2: Generalized pseudo-code of DE algorithm

Presently, several variants of DE are already available, and they differ in vector which is being perturbed and number of difference vectors considered for perturbation [43]. Also, another key difference exists in the type of crossover: binomial or exponential. The *DE/x/y/z* represents strategy utilized by DE algorithm, here x specifies the vector to be mutated, y is number of difference vectors used, and z denotes the crossover type. In the present work, *DE/best/1/bin* scheme has been employed and it is briefed in next few sub-sections. In particular, DE maintains a population of constant size NP real-valued vectors, X_{i_g}.

$$\hat{P}_g = X_{i\_g} \qquad i = 1, 2, ..., NP, \;\; g = 1, 2, ..., Ge_{max} \tag{3.1}$$

And each vector X_{i_g} contains D real parameters:

$$X_{i\_g} = x_{j\_i\_g} \qquad i = 1, 2, ..., NP, \;\; j = 1, 2, ..., D \tag{3.2}$$

3.2.1 Initialization

This is a process of establishing a starting point of population for seeking the optimum. Usually, there is very less information regarding the location of global optimum within the given limits on decision variables. Therefore, it is a practice to choose the initial population randomly within the given boundary constraints:

$$\hat{P}_0 = x_{j\_i\_0} = rand_j(0,1) * \left(x_j^U - x_j^L\right) + x_j^L \tag{3.3}$$

Here, $rand_j$ *(0, 1)* refers to a uniformly distributed random value within [0.0, 1.0] which is chosen for each *j*. Figure 3.3 illustrates equations (3.1)-(3.3). The "X" sign represents the endpoints of the population vectors.

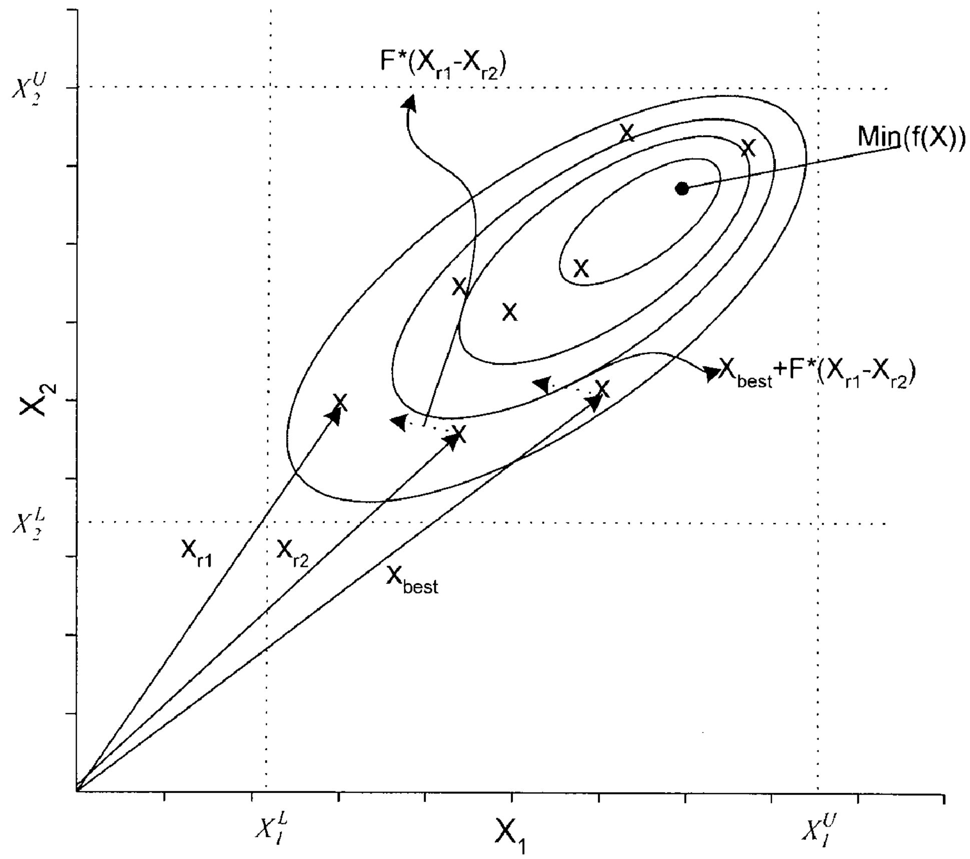

Fig.3.3: Illustration of initial population and mutation mechanism of DE.

P_{CR} and NP need to be determined by trial-and-error after a few tests. As observed in literature, the typical values are NP=3XD...10XD, F= (0.60-0.80) and P_{CR}= (0.80-0.90).

3.2.4 Selection

One of the key reasons for robustness and faster convergence of DE algorithm is its selection process [35]. Here all solutions in the population are equally probable candidates for future generations irrespective of their fitness value. Thus, each individual of the temporary population (i.e. obtained after mutation and crossover) is compared with its equivalent in the current population, and the best amongst them is considered for next generation.

Next generation: $$\hat{P}_{g+1} = \left[X_{1\_g+1},...X_{i\_g+1},...X_{NP\_g+1}\right]^T \tag{3.6.a}$$

$$X_{i\_g+1} = \begin{cases} V_{i\_g+1} & if \;\; f(V_{i\_g+1}) < f(X_{i\_g}) \\ X_{i\_g} & Otherwise \end{cases} \tag{3.6.b}$$

3.3 CONSTRAINT HANDLING

3.3.1 Boundary constraints

In a boundary constrained problem, it is necessary to ensure that design variables lie within the permitted range. An easiest way to assure this is to replace the parameter value that violates boundary constraint to the limiting value:

$$v_{j\_i\_g+1} = \begin{cases} x_j^L & \text{if } \;\; v_{j\_i\_g+1} < x_j^L \\ x_j^U & \text{if } \;\; v_{j\_i\_g+1} < x_j^U \\ v_{j\_i\_g+1} & Otherwise \end{cases} \tag{3.7}$$

Where, $i \in \{1, 2,..., NP\}, j \in \{1, 2,..., D\}$

Another simple but inefficient method to reproduce violating design variables, is according to equation (3.5).

3.3.2 Constraint functions

In the literature, various penalty function methods have been applied with DE for handling of constraint functions [41], [42]. The constraint function introduces a distance measure from the feasible region, thus the penalty function approach is known as soft constraint approach. In the simplest form, the function value $f_P(X)$ to be minimized is evaluated by penalizing the actual objective function *f(X)* value with weighted sum of constraint violations:

$$f_P(X) = f(X) + \sum_{j=1}^{m} W_j * \max(0, g_j(X)) \tag{3.8}$$

In (3.8), *m* is the total number of constraints of type $g_j(X) > 0$ and W_j is the weighting factor reflecting relative importance of the constraints. The penalty function approach effectively converts a constrained optimization problem into an unconstrained one, thus throughout the optimization $f_P(X)$ is used instead of *f(X)*.

3.4 HANDLING INTEGER AND DISCRETE VARIABLES

Originally, when DE was introduced it was meant for searching global optimum in a continuous space [33], [38], [41]. However, it is rather easy to modify DE to handle discrete or integer type of design variables. This is achieved by using the discrete/integer value only during function evaluation, although DE itself internally is still working with floating-point values. Therefore, DE works with a population of continuous variables regardless of the design variable type. This is essential to maintain the robustness of algorithm and also the diversity of population [33]. Thus,

$$x_i = \begin{cases} x_i & \text{for continous } x_i \\ DIS(x_i) & \text{for discrete } x_i \quad \forall i = 1,2,\dots,D \\ INT(x_i) & \text{for integer } x_i \end{cases} \tag{3.9}$$

DIS (.), INT (.) are subroutines for converting a real value into an equivalent discrete, integer value respectively. In addition, suitable minor modifications are also carried out during initialization process, as in [33], [41].

3.5 CONCLUSION

It is evident from the discussions above that DE is a relatively simple, easy to implement algorithm that can handle discrete and/or integer variables and nonlinear constraints elegantly. Simple soft constraint based approach itself is sufficient to handle constraint functions. Even in cases of no feasible solutions within the search space, DE algorithm is still able to find the nearest feasible solution. In this context, a brief insight into DE algorithm was presented in this chapter.

Although DE algorithm has been tested on various benchmark and practical problems, its applicability in the arena of electrical engineering is yet to be explored. In this reported work, DE and a modified DE algorithm are utilized and tested for their effectiveness in obtaining optimal relay coordination. The complete investigation of DE algorithm applied to relay coordination problem is presented in next chapter.

CHAPTER - 4

A DIFFERENTIAL EVOLUTION APPROACH FOR OPTIMAL RELAY COORDINATION

4.1 INTRODUCTION

In a largely interconnected power network, satisfying all the selectivity constraints simultaneously is a tedious job. However, researchers have been successful in tackling this infeasibility problem through various simplex-based linear, non-linear, network decomposition methods and artificial intelligence techniques [5]-[9], [12]-[14], [25]-[29]. Actually, each DOCR allows a continuous TDS and a discrete PS. Hence, the resultant problem of relay coordination is inherently MINLP problem, and obtaining a good feasible solution within acceptable computational time is tough. This chapter compiles the investigations performed to simultaneously optimize TDS and PS in a non-linear environment. In this analysis, a global optimization approach and a slight variant of the same have been investigated for coordinating relays of 6-bus (Fig. A.1), IEEE 14-bus (Fig. B.1) and IEEE 30-bus systems (Fig. C.1). Coordination is performed using conventional objective function (OBJ_{nr_fr}) considering the nominal state of power network.

The total selectivity constraints generated for all the test systems is given in Table. 4.1. Among all these constraints, few of them can be relaxed based on coordination philosophy of DOCRs [5], [6], [9], [17]. Criterions for relaxing such constraints are as under:

a) If fault current falls below pickup current of the DOCR

b) Direction of fault current and the associated relay are opposite to each other

Table.4.1: Details of selectivity constraints excluded during analysis

Test system	Total no. of decision variables	Total no. of selectivity constraints generated	Total no. of constraints to be satisfied in optimization
6-bus	28	48	38
14-bus	80	184	150
30-bus	164	400	348

Majority of the constraints are relaxed due to criteria (a), and the detailed analysis and the results obtained are discussed in the following sections.

Two approaches are proposed in the current work: non-adaptive DE (NADE) based coordination and adaptive DE (ADE) based coordination. Here, NADE is the simple DE with suitable modifications to handle discrete PS and soft non-linear constraints. Whereas, ADE approach is slightly a modified version of NADE as one of the input parameter to NADE algorithm is made adaptive. Simulation results reveal that NADE and ADE were fast converging and produced repetitive results. However, it was observed that ADE approach converged to a better solution with significant reductions in the primary operating time of relays. The detailed advantages of proposed approaches over SQP based coordination of [5], [6] has also been illustrated using 6-bus sample system.

4.2 ADAPTIVE DIFFERENTIAL EVOLUTION ALGORITHM

The performance of DE is largely governed by the values of control parameters [36]-[39], mainly by the scaling factor *F*. Choosing an appropriate value of *F* is a tedious trial and error task and also depends on the considered problem. Further, for adjusting such an parameter, the user has to depend on his experience or on the values present in literature. Therefore, to avoid such an inconvenience, a deterministic way of parameter control for adjusting the scaling factor has been proposed.

On application of NADE to the current coordination problem, it was observed that there was slow progress towards the convergence as the iterations increased. This might be due to the small search space and the solutions may be oscillating near the minima owing to large value of *F*. As a result, in ADE to tackle such a problem, *F* is continuously updated according to (4.1) at each generation.

$$F_g = F_U - \left[\frac{F_U - F_L}{Ge_{MAX}} \right] * g \tag{4.1}$$

The significant role of the proposed modification is to facilitate better exploration of search space. Hence, in ADE a large value of *F* during the initial generations assists in exploring the entire search space whereas a smaller value of *F* at later generations facilitates in the fine tuning of candidate solutions.

4.3 SIMULATION RESULTS

4.3.1 Study parameters

The applicability of the two variants of DE i.e. NADE and ADE for solving the relay coordination problem, with PS as discrete entity was carried out. In the case of 6-bus system, two PS settings were considered and for the other two systems six different PS settings were assumed. For all the test systems, an overload factor of 1.25 and a CTI of 0.20 sec were used [1], [17], [31].

Selection of proper value of the control parameters is essential for obtaining accurate results. In this regard, several trial runs were performed for different values of scaling factor (F) in the range [0.20, 0.80]. Finally, the value of the objective function was found to be minimum at F=0.6. Hence, this value was preferred for NADE. In ADE case F_U and F_L were selected as 0.80 and 0.20 respectively. The crossover probability (P_{CR}) of 0.90 was considered for both NADE and ADE for all the test systems. The NADE and ADE were experimented with different population sizes keeping the maximum number of generations constant and the best results were obtained for parameters presented in Table.4.2.

Table.4.2: Population size and maximum no. of generations used

Test system	Population Size	Maximum no. of generations
6-Bus	100	5000
14-Bus	200	10000
30-Bus	350	15000

4.3.2 Application of proposed approaches on 6-bus system

The 6-bus test system was extracted from [31], and it consists of 14 DOCRs totally accounting for 28 decision variables to be optimized. The problem was solved by NADE and ADE, the optimal relay settings obtained for the relays is presented in Table.4.3. Table.4.3 also presents the results obtained from the MATLAB Sequential Quadratic Programming (SQP) procedure [31]. In case of SQP results the PS setting have been rounded to the nearest available discrete setting. Interestingly, it was observed that on rounding off of the settings the optimal solution obtained becomes infeasible as one of the coordination constraint is violated. The value of the selectivity constraint which was violated is presented in Table.4.4. Whereas, NADE and ADE approaches handled such a infeasibility problem with slight sacrifice in the objective function value.

Table.4.3: Optimal relay settings for 6-bus sample system given in [31]

Relay (i)	MATLAB SQP (after rounding)		NADE		ADE	
	TDS_i	PS_i	TDS_i	PS_i	TDS_i	PS_i
1	0.1014	1.50	0.1173	1.25	0.1151	1.25
2	0.1863	1.50	0.2082	1.25	0.1863	1.50
3	0.0791	1.50	0.0998	1.25	0.0967	1.25
4	0.1006	1.50	0.1126	1.25	0.1006	1.50
5	0.0500	1.25	0.0500	1.25	0.0500	1.25
6	0.0500	1.50	0.0500	1.50	0.0582	1.25
7	0.0500	1.25	0.0500	1.25	0.0500	1.25
8	0.0500	1.25	0.0500	1.25	0.0500	1.25
9	0.0500	1.25	0.0500	1.25	0.0500	1.25
10	0.0500	1.50	0.0671	1.25	0.0518	1.50
11	0.0650	1.50	0.0844	1.25	0.0650	1.50
12	0.0505	1.50	0.0528	1.50	0.0513	1.50
13	0.0500	1.50	0.0589	1.25	0.0500	1.50
14	0.0708	1.50	0.0930	1.25	0.0708	1.50
OBJ_{nr_fr} Value	**10.2176**		**10.6983**		**10.3464**	
Remark	**Infeasible solution**		**Feasible solution**		**Feasible solution**	

Table.4.4: Constraint violated due to rounding off of PS setting in the solution obtained with MATLAB SQP

Constraint No.	Violation
1	-0.00553

Table.4.5 gives the comparison of the results obtained by different approaches. It is implicit that the ADE results are in close agreement with the once obtained by MATLAB SQP subroutine. The convergence curve of NADE and ADE for the 6-bus system is presented in Fig.4.1. It was observed that NADE reached convergence by 836th iteration and ADE converges by 1414th iteration. However, ADE results in minimum objective function value, thus resulting in lesser operating time of the relays. The application of ADE also avoids the usage of larger population size. But here, for the sake of comparison of effectiveness of the proposed adaptive approach, same population size (NP) was maintained.

Table.4.5: Comparison of directional overcurrent relay coordination results

Performance Index	**MATLAB SQP**	**NADE**	**ADE**
Primary Relays Operating Time (sec.)			
a) Mean	0.3649	0.3821	0.3695
b) Standard Deviation	0.1183	0.1213	0.1173
Backup Relays Operating Time (sec.)			
a) Mean	0.7252	0.8778	0.7191
b) Standard Deviation	0.2537	0.6314	0.2583

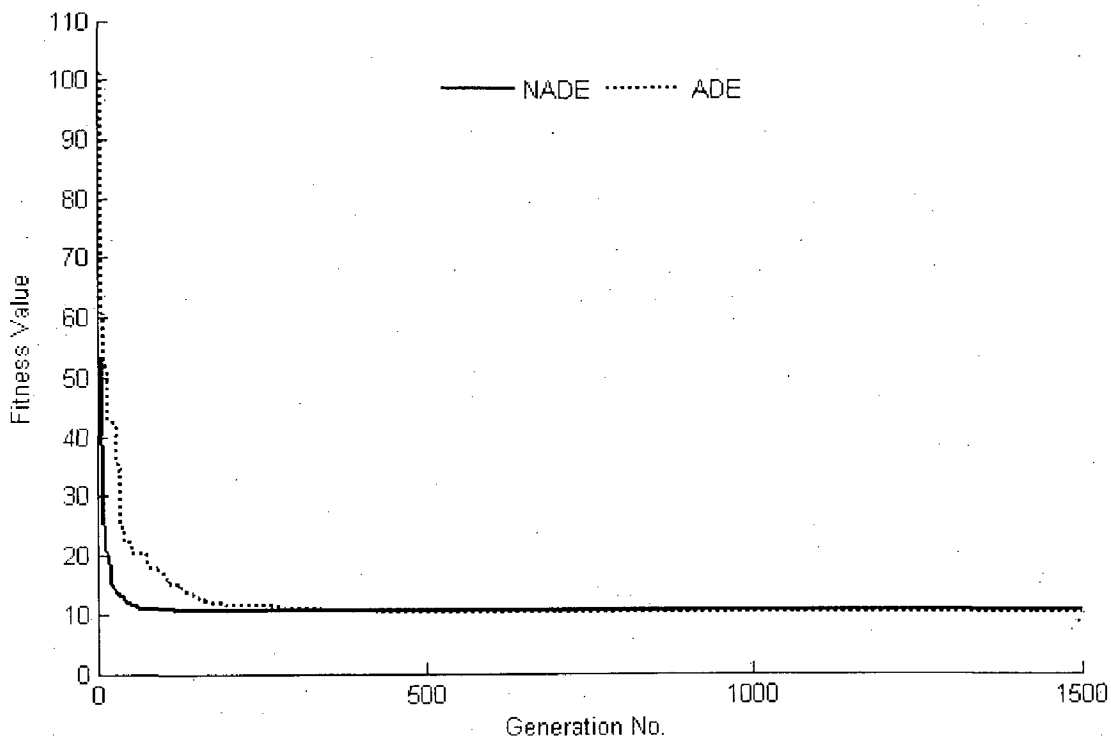

Fig.4.1: DE convergence curve for 6-bus sample system

Table.4.6 presents the operating times of concerned primary and its backup for both close-in and far-bus faults. Suitable comments have also been incorporated for better understanding of status of the corresponding selectivity constraint.

Table.4.6: Primary and backup relay operating time for all possible near-end and far-end faults

Fault location near relay	Type of fault	Primary relay number	Primary relay operating time in seconds			Backup relay number	Backup relay operating time in seconds			Remarks
			Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm		Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm	
1	Close-in	1	0.2629	0.2840	0.2785	8	0.5536	0.5536	0.5536	Constraint satisfied
						11	4.3002	2.0454	4.3002	Constraint satisfied
	Far-bus	2	0.6543	0.6677	0.6542	3	*	*	*	*Relay 3 sees I < I_{pck}
						5	DR	DR	DR	DR - Relay 5 directionally restrained
2	Close-in	2	0.4646	0.4860	0.4646	3	0.6650	0.6860	0.6647	Constraint satisfied
						5	*	*	*	*Relay 5 sees I < I_{pck}
	Far-bus	1	0.3713	0.3909	0.3833	8	1.1817	1.1817	1.1817	Constraint satisfied
						11	DR	DR	DR	DR - Relay 11 directionally restrained
3	Close-in	3	0.2955	0.3386	0.3281	10	0.5098	0.5388	0.5281	Constraint satisfied
						13	0.6558	0.5740	0.6558	Constraint satisfied
	Far-bus	4	0.3982	0.4026	0.3980	1	0.8508	0.8050	0.7899	Constraint satisfied
						5	*	*	*	*Relay 5 sees I < I_{pck}
4	Close-in	4	0.3113	0.3213	0.3112	1	0.5114	0.5212	0.5114	Constraint satisfied
						5	*	*	*	*Relay 5 sees I < I_{pck}
	Far-bus	3	0.3886	0.4332	0.4197	10	0.7059	0.6904	0.7313	Constraint satisfied
						13	*	*	*	*Relay 13 sees I < I_{pck}

Fault location near relay	Type of fault	Primary relay number	Primary relay operating time in seconds			Backup relay number	Backup relay operating time in seconds			Remarks
			Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm		Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm	
5	Close-in	5	0.2205	0.2205	0.2205	12	0.4462	0.4665	0.4533	Constraint satisfied
						14	0.7407	0.7621	0.7407	Constraint satisfied
	Far-bus	6	0.3650	0.3650	0.3559	1	*	*	*	*Relay 1 sees I < I_{pck}
						3	*	*	*	*Relay 3 sees I < I_{pck}
6	Close-in	6	0.1952	0.1952	0.2056	1	0.6604	0.6509	0.6387	Constraint satisfied
						3	0.7879	0.7867	0.7623	Constraint satisfied
	Far-bus	5	0.4429	0.4429	0.4429	12	1.5532	1.6239	1.5778	Constraint satisfied
						14	*	*	*	*Relay 14 sees I < I_{pck}
7	Close-in	7	0.5354	0.5354	0.5354	2	0.7735	0.7774	0.7735	Constraint satisfied
						11	0.7358	0.7354	0.7358	Constraint satisfied
	Far-bus	8	0.3667	0.3667	0.3667	No backup exists				
8	Close-in	8	0.3233	0.3233	0.3233	No backup exists				
	Far-bus	7	0.6153	0.6153	0.6153	2	0.8154	0.8152	0.8154	Constraint satisfied
						11	0.8527	0.8226	0.8527	Constraint satisfied
9	Close-in	9	0.2470	0.2470	0.2470	4	0.4472	0.4470	0.4472	Constraint satisfied
						13	0.4752	0.4472	0.4752	Constraint satisfied
	Far-bus	10	0.4269	0.4670	0.4422	No backup exists				
10	Close-in	10	0.3827	0.4266	0.3964	No backup exists				

Fault location near relay	Type of fault	Primary relay number	Primary relay operating time in seconds			Backup relay number	Backup relay operating time in seconds			Remarks
			Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm		Using MATLAB toolbox	Using NADE algorithm	Using ADE algorithm	
	Far-bus	9	0.2715	0.2715	0.2715	4	0.4867	0.4822	0.4867	Constraint satisfied
						13	0.5328	0.5183	0.5732	Constraint satisfied
11	Close-in	11	0.3705	0.4175	0.3703	6	0.6605	0.6605	0.5702	Constraint satisfied
						14	0.5703	0.6172	0.5703	Constraint satisfied
	Far-bus	12	0.2942	0.3074	0.2989	2	6.5212	3.8016	6.5212	Constraint satisfied
						8	0.8257	0.8257	0.8257	Constraint satisfied
12	Close-in	12	0.2091	0.2184	0.2124	2	0.9312	0.9176	0.9312	Constraint satisfied
						8	0.4696	0.4696	0.4696	Constraint satisfied
	Far-bus	11	0.5632	0.5946	0.5629	6	9.7303	9.7303	1.8623	Constraint satisfied
						14	0.9593	0.9284	0.9593	Constraint satisfied
13	Close-in	13	0.2163	0.2281	0.2163	6	0.8565	0.8565	0.6873	Constraint satisfied
						12	0.4098	0.4284	0.4163	Constraint satisfied
	Far-bus	14	0.4112	0.4678	0.4113	4	3.8467	2.1513	3.8467	Constraint satisfied
						10	1.3475	1.0594	1.3960	Constraint satisfied
14	Close-in	14	0.2699	0.3215	0.2699	4	0.5500	0.5371	0.5500	Constraint satisfied
						10	0.6053	0.6156	0.6271	Constraint satisfied
	Far-bus	13	0.3440	0.3424	0.3440	6	*	*	*	*Relay 6 sees I < I_{pck}
						12	0.7654	0.8003	0.7775	Constraint satisfied

4.3.3 Application of proposed approaches on IEEE 14-bus system

Altogether 184 coordination constraints were generated for the normal state of IEEE 14-bus system, corresponding to all the possible close-in and far-end faults on the system. The network details were taken from [44], and are presented along with a single line diagram in appendix-B. Totally 34 constraints were relaxed based on the criteria mentioned in section 4.1. Table.4.7 presents the optimal relay settings obtained for this system using both the proposed approaches.

4.3.4 Application of proposed approaches on IEEE 30-bus system

Totally 400 selectivity constraints were generated for the nominal state of IEEE 30-bus system, corresponding to all the possible near-end and far-end faults on the system. The network details were taken from [44], and are presented along with a single line diagram in appendix-C. Out of 400 constraints, 52 were relaxed based on the criteria mentioned in section 4.1. Table.4.8 presents the optimal relay settings obtained for this system using both the proposed approaches.

Table.4.7: Optimal relay settings obtained from NADE and ADE for IEEE 14-bus system

Relay (i)	NADE		ADE	
	TDS_i	PS_i	TDS_i	PS_i
1	0.0500	2.00	0.0500	1.25
2	1.0999	2.00	0.1072	2.00
3	0.0500	1.10	0.0500	1.10
4	0.0500	1.10	0.0500	1.10
5	0.0500	1.55	0.0500	1.40
6	0.0500	1.40	0.0500	1.40
7	0.0500	1.40	0.0500	2.00
8	0.0807	1.25	0.0888	1.25
9	0.0669	1.25	0.0500	1.40
10	0.0757	1.85	0.0782	2.00
11	0.0755	1.70	0.0908	1.25
12	0.2160	1.10	0.2352	1.10
13	0.0790	2.00	0.1056	1.70
14	0.0887	1.55	0.1059	1.40
15	0.1152	1.10	0.0760	2.00
16	0.1710	2.00	0.2480	1.10
17	0.0954	1.10	0.0549	2.00
18	0.2211	1.25	0.2300	1.10
19	0.1172	1.25	0.0934	1.85
20	0.0796	2.00	0.1064	1.55
21	0.2307	1.10	0.1997	1.40
22	0.4046	1.10	0.3669	1.40
23	0.0500	1.10	0.0500	2.00
24	0.3783	1.25	0.3526	1.55
25	0.0500	1.85	0.0500	1.10
26	0.2621	1.85	0.2496	2.00
27	0.3732	1.10	0.2897	1.85
28	0.0500	1.10	0.0500	1.10
29	0.0821	2.00	0.0944	1.55
30	0.3152	1.10	0.3035	1.10
31	0.2440	1.10	0.1832	2.00
32	0.4713	1.10	0.4492	1.10
33	0.2714	1.10	0.2613	1.10
34	0.2310	1.10	0.1947	1.70
35	0.3070	2.00	0.3530	1.10
36	0.3869	1.10	0.3157	1.85
37	0.2048	1.10	0.1934	2.00
38	0.4235	1.40	0.4510	1.10
39	0.1411	2.00	0.1741	1.10
40	0.3288	2.00	0.3410	1.70
OBJ_{nr_fr}	**35.4047**		**34.9528**	

Table.4.8: Optimal relay settings obtained from NADE and ADE for IEEE 30-bus system

Relay (i)	NADE		ADE	
	TDS_i	PS_i	TDS_i	PS_i
1	0.0555	1.10	0.0500	1.10
2	0.0500	1.10	0.0500	1.10
3	0.0500	1.25	0.0546	1.10
4	0.0694	1.70	0.0503	2.00
5	0.0500	1.70	0.0500	1.55
6	0.1251	1.85	0.1886	1.10
7	0.1090	1.10	0.1098	1.10
8	0.0677	1.40	0.0500	1.70
9	0.0500	1.10	0.0500	1.10
10	0.1361	1.10	0.0554	2.00
11	0.0669	1.10	0.0500	1.40
12	0.1489	1.10	0.1470	1.10
13	0.2051	1.10	0.1949	1.10
14	0.1752	1.25	0.1739	1.25
15	0.1359	1.10	0.1010	2.00
16	0.3472	1.10	0.2634	2.00
17	0.1674	1.40	0.1664	1.40
18	0.1780	1.10	0.1695	1.10
19	0.2181	1.55	0.2778	1.10
20	0.3049	1.55	0.2636	2.00
21	0.1765	1.10	0.1737	1.10
22	0.2803	1.70	0.3345	1.10
23	0.0898	1.55	0.1276	1.10
24	0.2444	1.70	0.2677	1.40
25	0.3654	2.00	0.4233	1.25
26	0.0500	1.10	0.0500	1.10
27	0.1210	2.00	0.1196	2.00
28	0.4238	1.10	0.3545	1.40
29	0.0752	2.00	0.1481	1.10
30	0.2611	1.10	0.2443	1.10
31	0.5642	1.25	0.4577	1.85
32	0.0500	1.10	0.0500	2.00
33	0.0500	2.00	0.0749	1.25
34	0.4008	2.00	0.3831	2.00
35	0.0887	2.00	0.0830	2.00
36	0.4265	1.25	0.4226	1.10
37	0.3538	1.10	0.2459	2.00
38	0.6565	1.10	0.5868	1.25
39	0.2179	1.40	0.2537	1.10
40	0.5988	1.40	0.5822	1.25
41	0.4691	1.85	0.5048	1.10

Relay (*i*)	NADE		ADE	
	TDS_i	PS_i	TDS_i	PS_i
42	0.6804	1.10	0.6251	1.10
43	0.2993	1.25	0.2871	1.25
44	0.6193	1.10	0.5740	1.10
45	0.5096	1.10	0.4110	2.00
46	0.6446	1.10	0.5885	1.10
47	0.4043	1.85	0.4659	1.10
48	0.3983	1.10	0.3120	1.55
49	0.2553	1.40	0.1849	2.00
50	0.5316	1.10	0.5191	1.10
51	0.4793	1.10	0.3378	2.00
52	0.5742	1.10	0.5474	1.10
53	0.0935	1.40	0.0743	1.55
54	0.4132	1.85	0.4335	1.40
55	0.1446	1.40	0.0843	2.00
56	0.3585	2.00	0.4285	1.10
57	0.3684	1.10	0.3327	1.10
58	0.7617	1.10	0.6070	2.00
59	0.4298	1.10	0.2999	2.00
60	0.4505	1.10	0.4272	1.10
61	0.2847	1.25	0.2247	1.85
62	0.5646	1.10	0.4825	1.40
63	0.5974	1.85	0.5438	1.85
64	0.4399	1.25	0.4236	1.10
65	0.4873	2.00	0.5499	1.10
66	0.3830	1.40	0.3685	1.55
67	0.5407	1.25	0.5415	1.10
68	0.0500	1.85	0.0500	1.10
69	0.5148	1.25	0.5166	1.10
70	0.2062	1.40	0.2202	1.10
71	0.3004	1.85	0.3844	1.10
72	0.0739	1.10	0.0500	1.40
73	0.0500	1.10	0.0500	1.10
74	0.1732	1.40	0.1463	2.00
75	0.0500	1.10	0.0500	1.10
76	0.1481	1.25	0.1237	1.85
77	0.1026	1.70	0.1291	1.10
78	0.1394	1.10	0.1394	1.10
79	0.5814	1.10	0.6312	1.10
80	0.8414	1.10	0.7954	1.40
81	0.0830	1.70	0.0629	2.00
82	0.3581	1.55	0.4102	1.25
OBJ_{nr_fr}	**108.5650**		**103.5055**	

4.4 PERFORMANCE COMPARISON OF NADE AND ADE APPROACHES

The effectiveness of proposed approaches was evaluated with respect to the convergence speed, final objective function value, and certain other performance indices used for comparing relay coordination techniques [45], [45]. The summary of such a comparison is given in Table.4.9. It is evident from Table.4.9 that as the search space narrows ADE is capable of searching better solutions quickly. In the ADE approach, significant improvements were also observed in operating times of primary relays as well as the backup relays. These reductions are suggestive of improved effectiveness of the backup protection. In the case of 14-bus test system out of the total 78 fault cases, reduction of operating time was observed for 44 cases and no change in operating time was observed in 8 cases. Similarly, in 30-bus system comprising of 164 fault cases, reduced operating time was observed in 122 cases and no change in operating time was observed in 12 cases. Table.4.10 lists out the operating times of few of the primary relays in which significant improvements were observed for IEEE 30-bus test system.

Table.4.9: Comparison of directional overcurrent relay coordination results

Performance Index	IEEE 14-bus system		IEEE 30-bus system	
	NADE	ADE	NADE	ADE
Sum of primary operating time	35.41	34.95	108.57	103.51
Iteration no.	8768	6589	14955	9728
Primary Relays Operating Time (sec.)				
a) Mean	0.4539	0.4481	0.6620	0.6311
b) Standard Deviation	0.2113	0.2061	0.3158	0.2941
Backup Relays Operating Time (sec.)				
a) Mean	0.9225	0.9657	1.2480	1.1940
b) Standard Deviation	0.3972	0.4630	0.6104	0.5703

Table.4.10: Operating time of primary relays which were significantly improved in IEEE 30-Bus Test System

Relay No.	Type of fault	Operating time obtained from NADE approach (in sec)	Operating time obtained from ADE approach (in sec)	Reduction in operating time (in sec)
10	Far-end	0.6429	0.4457	-0.1972
10	Near-end	0.4158	0.2322	-0.1836
42	Far-end	1.2508	1.1492	-0.1016
51	Near-end	1.1099	0.9881	-0.1218
51	Far-end	1.1826	1.0703	-0.1123
59	Near-end	0.9617	0.8407	-0.1210

4.5 CONCLUSION

In this chapter, an investigation of two variants of DE was carried out. It was found that the proposed approaches were successful in obtaining a feasible solution. Although, NADE approach obtained an optimal solution, the coordination quality was sacrificed to a small extent. The chapter also describes the ability of ADE approach to obtain better optimal solution during small search space. Therefore, it is concluded that the ADE based approach has the potential of being a novel alternative for relay coordination in large interconnected systems.

The coordination performed until now considered only the normal selectivity constraints. But in largely interconnected power networks, either due to inherent nature of the system or due to incorrect setting of relays, a relay may trip in response to a fault which occurs outside its region of influence. Such kinds of trips are known as sympathy trips. These nuisance trippings affect the optimum system performance by removing additional circuit. Hence, such trippings needs to be identified and suitable measure need to be taken to minimize or even eliminate them. As a result, efforts have been made to understand and resolve the sympathetic tripping problem in subsequent chapter.

CHAPTER - 5

INVESTIGATION OF SYMPATHETIC TRIPPING OF *DOCRs*

5.1 INTRODUCTION

Correct operation of relay indicates the isolation of troubled area within acceptable time limits through accurate operation of at least one primary relay. Generally, close to 99% of relay operations are accurate and essential [3]. In contrast, an incorrect operation is resultant of a malfunction, or an unanticipated/unplanned action. The key reasons for incorrect operation can be one or more of the following.

- Misapplication of relays
- Incorrect settings
- Personnel errors
- Equipment failures (such as relay, breaker, CT, station battery etc)

It is practically impossible to anticipate and provide protection against each and every possible power system disturbance. Even the best planned and designed system is subject to potential situations that may not be protected against or have remained undetected.

Prerequisite of a well coordinated system is that only the primary relay for a given fault has to trip and minimize any further damage [2], [3], and backup relay should trip only if primary relay fails to operate. However, sometimes because of inherent nature of complex interconnections in system or due to inappropriate relay settings, a relay may trip even for faults beyond its region of influence [3], [47]. These unnecessary trippings are commonly known as sympathetic/nuisance tripping. A critical survey conducted by IEEE power system relaying committee mentions several sympathetic tripping of relays [48]. Such an unnecessary tripping can originate under any of the system conditions mentioned below [47]-[50].

- Large inrush current (i.e. in large transformers, motors or feeder capacitor banks)
- Cold load pickup condition

- Redistribution of fault current
- Inappropriate relay settings
- Possible changes in generation/load level or system contingencies

An extensive survey conducted on incorrect protection operations on an electric power network owned by Skydkraft (in Sweden) is reported in [50]. This critical survey was based on disturbance and special investigation reports for the period 1976-2002. According to this report, nearly 60% of nuisance trippings were due to unwanted operation (i.e. non-selective operation) of protective relays.

Sympathetic trippings are of serious concern as they adversely affect system performance and reliability [50]-[52]. Such nuisance trippings would deteriorate system security level, and if undetected, may even lead to cascaded trippings and blackout [52].

5.2 CLASSIFICATION OF SYMPATHY TRIPS

After performing extensive studies, researchers [47] have classified the tendency of sympathy trips into following four categories:

a) Primary relay fails to trip, because it sees the fault current in opposite direction
b) Fault current seen by primary relay is below its I_{pck} setting
c) Backup relay operates prior to primary relay
d) Before the operation of primary and its backup relay, some other relay in the system operates

The first two type of sympathy trips are difficult to treat. Although, such situations can be easily detected, they can not be avoided. For all such situations, autoreclosing of breakers is the only viable answer. The other two types of sympathy trips can be avoided either by adopting adaptive protection schemes or by performing optimal coordination with inclusion of additional constraints accounting for sympathy trips.

Recently, in a noticeable development [5], a strategy has been evolved to determine and avoid the occurrence of sympathy trips. For this purpose, the researchers have studied the complex interrelations of operating time among different relays during every possible fault. For a given fault location, every relay experiencing the fault current greater than it's I_{pck} was treated as a possible candidate for sympathy trip, and its operating time was monitored. No sympathy trips occurred in the system if operating time of such relays under observation is greater than the operating time of designated primary and backup relays. The strategy developed to avoid sympathy trips in [5] is mentioned below:

"If the current seen by any relay in the system other than the designated primary and backup relays is more than its setting current then its operating time should be more than that of the designated primary and backup relays to the fault location under consideration. These constraints should be applied to cover all the fault locations for the relay under consideration, so that tendency for sympathy trip might be stopped for this relay for all the fault locations. In the similar manner, if constraints are imposed on all the relays other than the designated primary and backup relays, all the sympathy trips may be avoided in the system".

Based on the above mentioned strategy, investigations were carried on IEEE 14-bus and 30-bus systems and the results obtained are discussed in the next section.

5.3 RESULTS

5.3.1 IEEE 14-Bus system

The optimal relay settings obtained for this test system given in Table.4.7 were tested for sympathy trips. Interestingly, there were four cases of sympathy trips in NADE approach against five in ADE approach. However, all these trips were not harmful to the system because they vanished once the redistribution of fault current was taken into account. Table.5.1 presents the operating times of primary relay and the possible sympathy tripping of relay for NADE and ADE approaches.

Sympathy trips were observed for faults near relay 25, 27, 28 and 31 in both the approaches, and an additional tripping case was seen for fault near relay 26 in ADE approach. Now, considering a fault near relay 25, the relay 39 trips prior to the designated far-end primary relay 26. However, relay 25 is the first to operate, and it opens the near-end breaker; this act would redistribute the fault currents in the system. Once this redistribution occurs the operating times of relays are recalculated and it is found that at this instant, relay 26 would operate ahead of relay 39. Hence, the possibility of sympathy trip is completely avoided due to redistribution of fault current.

Table.5.1: Operating time of relays for which sympathy trips were observed

Fault near relay no.	Fault type	Operating time of primary relay in seconds	Tripping relay no.	Operating time of tripping relay	Operating time of primary relay after redistribution of fault current	Operating time of tripping relay after redistribution of fault current
NADE Approach:						
Relay 25	Near-end	25 0.1206	39	0.7431	0.6966	3.7914
	Far-end	26 0.7587				
Relay 27	Near-end	27 0.2145	39	0.4808	0.6261	2.2591
	Far-end	28 0.7052				
Relay 28	Near-end	28 0.5705	39	0.5550	0.5216	0.9037
	Far-end	27 0.3549				
Relay 31	Near-end	31 0.3300	35	0.7897	0.7846	5.5411
	Far-end	32 0.8637				
ADE Approach:						
Relay 25	Near-end	25 0.1539	39	0.6261	0.6913	1.4088
	Far-end	26 0.7569				
Relay 26	Near-end	26 0.5971	39	0.5948	0.5598	0.6747
	Far-end	25 0.2393				
Relay 27	Near-end	27 0.1612	39	0.4547	0.6135	1.1675
	Far-end	28 0.6934				
Relay 28	Near-end	28 0.5577	39	0.5073	0.5088	0.7137
	Far-end	27 0.2304				
Relay 31	Near-end	31 0.3294	35	0.7364	0.7846	2.4861
	Far-end	32 0.8316				

5.3.2 IEEE 30-Bus system

The optimal relay settings given in Table.4.8 were also tested for possible sympathetic trips. It was found that out of 16 possible cases detected in ADE approach, six of the sympathy trips were inevitable. Similarly, in NADE approach, five cases of sympathy trips stayed among the total 13 possible identified cases. Table.5.2 summarizes all the sympathy trips which were identified to be harmful to optimal operation of system.

Table.5.2: Operating time of relays for which sympathy trips are inevitable

Fault near relay no.	Fault type	Operating time of primary relay in seconds	Tripping relay no.	Operating time of tripping relay	Operating time of primary relay after redistribution of fault current	Operating time of tripping relay after redistribution of fault current
NADE Approach:						
Relay 38	Near-end	1.0632	39	0.7964	--	--
	Far-end	0.9110				
Relay 52	Near-end	0.9010	57	0.8819	--	--
	Far-end	1.1826	61	0.8566	--	--
Relay 53	Near-end	0.3158	61	0.7702	1.0694	1.0548
	Far-end	1.1752				
Relay 54	Near-end	0.9986	61	0.8056	0.9850	0.9299
	Far-end	0.5050				
ADE Approach:						
Relay 38	Near-end	0.9818	39	0.8198	--	--
	Far-end	0.8228				
Relay 50	Near-end	0.9066	57	0.8613	--	--
	Far-end	0.8803				
Relay 51	Near-end	0.9883	57	0.9021	--	--
	Far-end	0.9194				
Relay 52	Near-end	0.8589	57	0.7964	--	--
	Far-end	1.0705	61	0.8201	--	--
Relay 54	Near-end	0.9506	61	0.7621	0.9388	0.9061
	Far-end	0.4364				

For faults near relays 38, 50, 51 and 52, it was noticed that some other relay operated well ahead of the designated primary relays. Whereas, in the other cases sympathy trip persisted even after the redistribution of fault current. Henceforth, the sympathy tripping occurring well ahead of primary relays would be termed as Type-I tripping and the other category of tripping would be recognized as Type-II tripping.

5.4 CONCLUSION

This chapter presented a brief overview of the problem of sympathetic tripping relays in large interconnected power networks. Various classifications of the tripping, reasons for such nuisance trips and possible solution strategies available in literature were also reviewed. Moreover, sympathy trips occurring ahead of primary relays or after redistribution of fault current were demonstrated with the help of standard test systems.

Although, optimal relay settings were obtained through a global search technique in the previous chapter, investigations reveal that even these settings were prone to nuisance trips. Hence, there is an immediate requirement to develop solution approaches to mitigate these unwanted trips. In this context, next chapter furnishes two simple solution strategies developed to avoid all such nuisance trips.

CHAPTER - 6

PREVENTION OF SYMPATHETIC TRIPPING OF *DOCRs* IN LARGE POWER NETWORKS

6.1 INTRODUCTION

The key objective of a well coordinated system is to assure maximum service continuity with minimum system disconnection. Hence, a selective operation of relays is essential to ensure a reliable power supply. However, assuring this for every conceivable system condition is not possible. Moreover, the present days deregulated electricity market enforces the utilities to strive to achieve the acceptable reliability levels. Therefore, unwanted tripping of relays in large power networks imposes additional restrictions and is a much more serious problem because it introduces multiple contingencies affecting the system security level [11].

As mentioned in previous chapter, few kinds of sympathy trips are inevitable. Nevertheless, in a latest development [51], researchers are successful in tackling the sympathy trips occurring before primary relays. Here, solution to the problem was obtained in two phase. In the first phase, coordination was performed using normal procedure and sympathy trips were identified. The final settings were obtained at the end of second phase after including additional constraints to accommodate sympathy trips. Three approaches have been investigated for tackling sympathy trips and one of them resulted in desired outcome. However, the proposed approaches used MATLAB SQP subroutine to obtain optimal settings and this requires a good initial guess to achieve desired result. Also, PS settings were considered as continuous; this may result in an infeasible solution on rounding.

The present work also adopts a two phase strategy to eliminate sympathy trips. However, discrete PS settings are considered and optimization is performed in first phase using a global optimization technique. In the second phase, coordination problem is reformulated as linear problem along with additional constraints for sympathy trips, and optimal settings here are acquired using dual simplex subroutine of Xpress-IVE package. The additional constraints to be introduced in second phase are described in next section.

6.2 ADDITIONAL SYMPATHY TRIPPING CONSTRAINTS

A brief review of additional constraints to be considered during optimization for removal of sympathetic tripping problem is described here. In [5], [51], researchers have classified the entire cases of sympathetic tripping into two categories as under:

- Some other relay operates prior to operation of designated backup relay
- The backup or some other relay in system operates ahead of primary relay

One of the major causes identified for sympathetic tripping is the redistribution of fault currents due to transient changes in network (i.e. due to operation of one primary relay whereas other is yet to operate). All such situations can be handled suitably by introducing additional constraints during optimization as proposed in [51]; these are expressed as in (6.1.a)-(6.2.b):

a) Operating ahead of primary as well as backup relays

$$\begin{aligned} &\text{if } OT^k > 0 \\ &\text{then } OT^k \geq Min\left\{\left(OT^m_{pri\_nr}, OT^{m_i}_{bck\_nr}\right), \left(OT^n_{pri\_fr}, OT^{n_j}_{bck\_fr}\right)\right\} \end{aligned} \tag{6.1.a}$$

$$\begin{aligned} &\text{and if } {}_{tr}OT^k > 0 \\ &\text{then } {}_{tr}OT^k \geq Min\left\{\left({}_{tr}OT^m_{pri\_nr}, {}_{tr}OT^{m_i}_{bck\_nr}\right), \left({}_{tr}OT^n_{pri\_fr}, {}_{tr}OT^{n_j}_{bck\_fr}\right)\right\} \end{aligned} \tag{6.1.b}$$

s.a. $i \in A_m$, $j \in B_n$

b) Operating prior to primary relays

$$\begin{aligned} &\text{if } OT^l > 0 \\ &\text{then } OT^l \geq Min\left(OT^m_{pri\_nr}, OT^n_{pri\_fr}\right) \end{aligned} \tag{6.2.a}$$

$$\begin{aligned} &\text{and if } {}_{tr}OT^l > 0 \\ &\text{then } {}_{tr}OT^l \geq Min\left({}_{tr}OT^m_{pri\_nr}, {}_{tr}OT^n_{pri\_fr}\right) \end{aligned} \tag{6.2.b}$$

6.3 PROPOSED APPROACHES

In the investigations performed, main aim was to eliminate sympathetic tripping of DOCRs. First phase ends with determination of optimal relay settings using ADE along with normal selectivity constraints. In the second phase, sympathy trips are initially identified and coordination problem is reformulated as an LPP with additional constraints accounting for sympathy trips. The solution for second phase is obtained using dual simplex subroutine of Xpress-IVE package. This procedure is selected as solution of phase-I is to be adjusted near by to satisfy few additional constraints. Two approaches have been investigated here and these differ in the objective function considered for optimization during first phase.

Approach-I:

- Phase-I: Minimize the objective function given by (2.6) based on near-end relays operating time subject to selectivity constraints ((2.9.a) and (2.9.b)) and bounds of (2.10.a)-(2.10.b) using ADE

Approach-II:

- Phase-I: Same as in approach-I except for that the objective function used here is given by (2.5)

For both the approaches, in phase-II a common procedure is adopted to obtain the final optimal relay settings, and is as follows.

- Phase-II: Reformulate the coordination problem as LPP as in (2.7). Minimize (2.7) subject to near-end and far-end fault constraints (i.e. (2.9.a) and (2.9.b)), bounds of (2.10.a)-(2.10.b) and sympathy trip constraints (i.e. (6.2.a) and (6.2.b)) using dual simplex method

6.4 RESULTS AND DISCUSSION

Several test runs were conducted to ascertain robustness of ADE algorithm, and it was found to give consistent results. The investigations carried out on IEEE 30-bus system have been reported here. Parallel lines existing in IEEE 30-bus network were replaced by equivalent single line and the equivalent single line diagram is given in Fig.C.1. Altogether, four hundred selectivity constraints are generated, and 79 of these were found invalid based on criteria mentioned in [5], [6], [17], [51].

6.4.1 Phase-I

The proposed approaches during this phase were described in previous section and the input parameters to ADE algorithm are same as mentioned in section 4.3.1.

- Approach-I:

Although a feasible solution was obtained in phase-I from ADE, it was observed that in eight cases there was sympathetic tripping. Six out of these eight were due to violation of constraint (6.2.a) and the other two were after redistribution of fault current (i.e. due to (6.2.b)). Operating times of relays and sympathetic tripping identified after phase-I of approach-I are given in Table.6.1. Interestingly, for near-end faults near relay 53 and 54, it is relay 53 which trips.

- Approach-II:

In this approach comparatively lesser number of sympathy trips was observed after first phase. Also, tripping in this approach was not of the same relay as seen in approach-I. The only sympathy trip observed was of relay 39 for a near-end fault occurring at relay 38, and it belongs to Type-II category.

6.4.2 Phase-II

Phase-II in both approaches is same and solution for this phase was obtained through dual simplex algorithm. Feasible solution was obtained for both approaches and no new sympathy trips were introduced after the second phase. The final optimal settings of relays obtained after each phase in both approaches are mentioned in Table.6.2.

Table.6.1: Sympathetic trippings identified at the end of phase-I

Fault near relay no.	**Fault type**	**Primary relay (Operating time in seconds)**	**Relay no. identified as sympathy trip (Operating time in seconds)**		**Type of tripping**
Phase-I of Approach-I:					
Relay 50	Near-end	50 (0.8912)	57 (0.7790)	61 (0.8727)	Type-I
	Far-end	49 (1.0083)			
Relay 51	Near-end	51 (1.0371)	57 (0.8159)	61 (0.9421)	Type-I
	Far-end	52 (0.9681)			
Relay 52	Near-end	52 (0.9044)	57 (0.7203)	61 (0.7701)	Type-I
	Far-end	51 (1.1234)			
Relay 53	Near-end	53 (0.2056)	61 (0.6751)	--	Type-II

Fault near relay no.	Fault type	Primary relay (Operating time in seconds)	Relay no. identified as sympathy trip (Operating time in seconds)		Type of tripping
	Far-end	54 (1.1662) (OT_{RFC}=1.0781)	(OT_{RFC}=1.008)		
Relay 54	Near-end	54 (1.0175) (OT_{RFC}=1.006)	* 61 (0.7135) (OT_{RFC}=0.8547)	--	Type-II
	Far-end	53 (0.3758)			
Phase-I of Approach-II					
Relay 38	Near-end	38 (1.0198) (OT_{RFC}=1.035)	39 (0.9284) (OT_{RFC}=0.7597)	--	Type-II
	Far-end	37 (0.8709)			

* OT_{RFC} gives the operating time of relay after redistribution of fault current.

Table.6.2: Optimal relay settings obtained for IEEE 30-bus system after each phase

Relay no.	Phase-I				Phase-II	
	Approach-I		Approach-II		Approach-I	Approach-II
	TDS	*PS*	*TDS*	*PS*	*TDS*	*TDS*
1	0.0659	1.10	0.0500	1.40	0.0659	0.0500
2	0.0500	1.10	0.0500	1.10	0.0500	0.0500
3	0.0500	1.25	0.0500	1.25	0.0500	0.0500
4	0.1161	1.10	0.1314	1.10	0.1161	0.1313
5	0.0500	1.85	0.0500	1.70	0.0500	0.0500
6	0.1808	1.10	0.1216	2.00	0.1801	0.1216
7	0.1090	1.10	0.1090	1.10	0.1090	0.1090
8	0.0500	1.70	0.1025	1.10	0.0500	0.1024
9	0.0500	1.25	0.0500	1.10	0.0500	0.0500
10	0.0584	2.00	0.0553	2.00	0.0582	0.0553
11	0.0570	1.40	0.0689	1.10	0.0571	0.0689
12	0.0757	2.00	0.0758	2.00	0.0752	0.0757
13	0.1990	1.10	0.1997	1.10	0.1981	0.1996
14	0.1294	1.85	0.2006	1.10	0.1287	0.2004
15	0.1411	1.10	0.1359	1.10	0.1411	0.1359
16	0.2905	1.85	0.2703	1.85	0.2892	0.2702
17	0.2048	1.10	0.1263	2.00	0.2036	0.1262
18	0.1641	1.40	0.1780	1.10	0.1641	0.1780
19	0.2381	1.55	0.2073	2.00	0.2364	0.2070
20	0.3545	1.10	0.3554	1.10	0.3519	0.3550

Relay no.	Phase-I				Phase-II	
	Approach-I		Approach-II		Approach-I	Approach-II
	TDS	*PS*	*TDS*	*PS*	*TDS*	*TDS*
21	0.1823	1.10	0.1827	1.10	0.1813	0.1825
22	0.2511	2.00	0.3479	1.10	0.2492	0.3478
23	0.1376	1.10	0.1379	1.10	0.1369	0.1378
24	0.3295	1.10	0.3347	1.10	0.3290	0.3342
25	0.4124	1.55	0.4687	1.10	0.4093	0.4686
26	0.0500	1.10	0.0500	1.10	0.0500	0.0500
27	0.1870	1.10	0.1873	1.10	0.1862	0.1872
28	0.4242	1.10	0.3566	1.55	0.4203	0.3565
29	0.1420	1.10	0.1569	1.10	0.1414	0.1567
30	0.2510	1.10	0.2522	1.10	0.2496	0.2520
31	0.4560	2.00	0.4582	2.00	0.4535	0.4578
32	0.0500	2.00	0.0500	1.10	0.0500	0.0500
33	0.0994	1.10	0.0999	1.10	0.0988	0.0998
34	0.4796	1.25	0.4837	1.10	0.4779	0.4824
35	0.1138	1.70	0.0856	2.00	0.1131	0.0856
36	0.4418	1.10	0.4419	1.10	0.4399	0.4416
37	0.3523	1.10	0.2814	1.70	0.3510	0.2812
38	0.5883	1.40	0.5357	2.00	0.5844	0.5351
39	0.2629	1.55	0.2873	1.10	0.2621	0.3908
40	0.6324	1.10	0.5215	2.00	0.6297	0.5215
41	0.4558	2.00	0.5285	1.10	0.4545	0.5283
42	0.6554	1.10	0.6591	1.25	0.6503	0.6584
43	0.2832	1.25	0.3265	1.10	0.2974	0.3265
44	0.5373	1.70	0.5675	1.40	0.5345	0.5674
45	0.4067	2.00	0.5249	1.10	0.4224	0.5249
46	0.5487	2.00	0.6369	1.10	0.5454	0.6367
47	0.4428	1.25	0.4975	1.10	0.4565	0.4973
48	0.3307	1.85	0.3926	1.10	0.3282	0.3925
49	0.2818	1.25	0.2115	1.85	0.2792	0.2115
50	0.4927	1.25	0.4547	1.85	0.5052	0.4546
51	0.3545	2.00	0.4831	1.10	0.3539	0.4830
52	0.5764	1.10	0.5679	1.10	0.5695	0.5677
53	0.0500	2.00	0.1308	1.10	0.0500	0.1307
54	0.5014	1.10	0.4870	1.25	0.5004	0.4869
55	0.1003	1.85	0.0868	2.00	0.0994	0.0868
56	0.4506	1.10	0.4035	1.55	0.4496	0.4034
57	0.3009	1.10	0.4143	1.10	0.3733	0.4142
58	0.7428	1.10	0.7201	1.40	0.7410	0.7198
59	0.3275	1.85	0.4218	1.10	0.3261	0.4216
60	0.4196	1.10	0.4672	1.10	0.4468	0.4671

Relay no.	Phase-I				Phase-II	
	Approach-I		Approach-II		Approach-I	Approach-II
	TDS	*PS*	*TDS*	*PS*	*TDS*	*TDS*
61	0.2021	2.00	0.2543	2.00	0.2374	0.2542
62	0.5131	1.40	0.5473	1.25	0.5116	0.5471
63	0.6637	1.10	0.6851	1.10	0.6613	0.6848
64	0.4012	1.25	0.4754	1.10	0.4353	0.4754
65	0.5848	1.10	0.6004	1.10	0.5831	0.6002
66	0.4062	1.10	0.4479	1.25	0.4062	0.4479
67	0.0500	1.10	0.0500	1.10	0.0500	0.0500
68	0.0500	1.10	0.0500	1.10	0.0500	0.0500
69	0.4360	2.00	0.5565	1.10	0.4349	0.5555
70	0.1780	2.00	0.2132	2.00	0.1780	0.2132
71	0.3957	1.10	0.4091	1.10	0.3914	0.4085
72	0.0500	1.55	0.0500	2.00	0.0500	0.0500
73	0.0500	1.10	0.0500	1.10	0.0500	0.0500
74	0.1901	1.10	0.1404	2.00	0.1901	0.1404
75	0.0500	1.10	0.0500	1.10	0.0500	0.0500
76	0.1561	1.10	0.1631	1.10	0.1561	0.1631
77	0.0975	1.85	0.1291	1.10	0.0975	0.1291
78	0.1319	1.25	0.1044	2.00	0.1319	0.1044
79	0.6213	1.10	0.6087	1.10	0.6181	0.6082
80	0.7947	1.55	0.7646	2.00	0.7874	0.7636
81	0.1281	1.10	0.0640	2.00	0.1277	0.0640
82	0.4396	1.10	0.4516	1.10	0.4358	0.4510
OBJ_{nr_fr}	**106.2760**		**108.7730**		**106.7110**	**108.9930**

Table.6.3 compares the two proposed approaches with respect to few of the performance measures. It is clear that approach-I gives a lower objective function value, but at an increased risk. Therefore, even with slightly higher objective function value, approach-II would be a better choice as per system security is concerned.

Table.6.3: Performance comparison of proposed approaches

Performance Index	Approach-I	Approach-II
Objective function value at optimal point (sec.)	106.711	108.993
Primary Relays Operating Time (sec.)		
a) Mean	0.6507	0.6646
b) Standard Deviation	0.3097	0.3159
Backup Relays Operating Time (sec.)		
a) Mean	1.2410	1.2740
b) Standard Deviation	0.6306	0.6902
Total no. of sympathy trips in phase-I	8	1

6.5 CONCLUSION

The additional constraints to accommodate sympathy trips were reviewed briefly in this chapter. Two different approaches were proposed to suitably tackle the sympathy trips in large power networks. The problem of sympathy trips was handled in two phases; in first phase optimization was performed using a global optimization technique and for later stage the results were obtained using linear programming method. The proposed approaches were demonstrated on IEEE 30-bus system and the results suggest that both were successful in removing sympathy trips occurring ahead of primary relays. Although, both approaches succeeded in handling sympathy trips, the final choice of approach has to be made after considering the number of sympathy trips introduced at the end of phase-I. Hence, it is concluded that approach-II is a better choice even though it results in higher value of performance function.

CHAPTER - 7

CONCLUSIONS AND FUTURE SCOPE

7.1 CONCLUSIONS

The optimal coordination of directional overcurrent relays in large interconnected power network is a tedious job. The complexity arises because it is a constrained mixed integer non-linear optimization problem. In literature, variety of conventional and topological techniques are available, but each of them suffer from some or the other drawback. A brief overview of few of the predominant solution techniques was presented in chapter-2. Most of these techniques are meant for coordination subject to normal coordination constraints and it does not ensure foolproof protection because sympathy trips are not considered. However, lately, the requirement for enhanced reliability of power supply has imposed additional pressure on utilities to minimize/eliminate unwanted tripping of relays. Therefore, there is an immediate need to evolve solution strategies to mitigate all such nuisance trips within the coordination phase.

The current thesis makes some contributions in the area of optimal relay coordination and few significant of them are summarized below:

- Development of a fully integrated software for performing optimal coordination of DOCRs
- Solution obtained from the software are much nearer to practical settings as discrete PS settings are considered
- Usage of a novel global optimization technique (i.e. DE) for solving the constrained mixed integer non-linear problem formulation of relay coordination
- Feasibility and applicability of two different variants of DE (i.e. NADE and ADE)
- Investigations to find the reasons for sympathy trips in large interconnected power networks

- Proposal and demonstration of two new approaches for complete removal of sympathetic tripping problem

7.2 SCOPE FOR FUTURE RESEARCH

This section presents the advancements that can be carried out in the arena of relay coordination for ensuring a secure and reliable power network. Some of the directions, which can be taken up for future research are listed below:

- Development of "Figure of Merit" as prepared in [53] to quantify the quality of coordination after inclusion of sympathy trips
- Evaluation of effects of sympathy trips with reference to severity of trip, loss of load, cost of interruption, number of customer affected etc
- Incorporation of cost of damages due to failure of protection
- Application of proposed techniques for coordinating real power systems comprising of FACTS devices
- Development of suitable solution technique to tackle sympathy trips within single phase along with additional constraints (6.1.a) and (6.1.b)
- Inclusion of single line contingencies and the respective transient configuration details during optimization
- Subsystem, decomposed or local optimization type of approaches can to be looked upon to achieve faster coordination for already operational systems with necessary checks for sympathy trips

BIBILIOGRAPHY

[1] Juan M. Gers and Edward J. Holmes, "Protection of Electricity Distribution Networks 2nd edition," IEE Power and Energy Series 47, ISBN 0–86341–357–9, Institution of Electrical Engineers, London, United Kingdom, 2004.

[2] A. G. Phadke and S. H. Horowitz, "Power system relaying," John Wiley & sons, Somerset, United Kingdom, 1995.

[3] J. Lewis Blackburn, "Protective Relaying: Principles and applications," Electrical Engg. and Electronics Series, New York, Marcel Dekker, 1998.

[4] Turan Gonen, "Electric Power Distribution System Engineering," ISBN 0–07–023707–7, McGraw–Hill Book Company, 1986.

[5] D. Birla, "Coordination of Directional Overcurrent Relays in Power Networks," Ph. D. Thesis, Department of Electrical Engineering, IIT Roorkee, 2006.

[6] D. Birla, R. P. Maheshwari and H. O. Gupta, "A New Non-linear Directional Overcurrent Relay Coordination Technique, and Banes and Boons of Near-end Faults Based Approach", IEEE Transactions on Power Delivery, Vol.–21, No.–3, pp. 1176–1182, April 2006.

[7] D. Birla, R. P. Maheshwari, and H. O. Gupta, "Time-Overcurrent Relay Coordination: A Review," International Journal of Emerging Electric Power Systems, Vol.-2, Issue-2, April 2005.

[8] A. J. Urdaneta, Ramon Nadira and L. G. Perez Jimenej, "Optimal Coordination of Directional Overcurrent Relays in Interconnected Power Systems," IEEE Transactions on Power Delivery, Vol.–3, No.–3, pp. 903–911, July 1988.

[9] H. K. Karegar, H. A. Abyaneh, V. Ohis and M. Meshkin, "Pre–processing of the Optimal Coordination of Overcurrent Relays," Electric Power Systems Research, Vol.–75, Issues 2–3, pp. 134–141, August 2005.

[10] IEEE Committee Report, "Computer Aided Coordination of Line Protection Schemes," IEEE Transactions on Power Delivery, Vol.–6, No.–2, pp. 575–583, April 1991.

[11] G. D. Rockefeller, C. L. Wagner and J. R. Linders, "Adaptive Transmission Relaying Concepts for Improved Performance," IEEE Transactions on Power Delivery, Vol.–3, No.–4, pp. 1446–1456, October 1988.

[12] N. A. Laway and H. O. Gupta, "A Method for Coordination of Overcurrent Relays in Interconnected Power Systems," Journal of the Institution of Engineers (IEJ), India, Vol.–74, pp. 59–65, August 1993.

[13] N. A. Laway and H. O. Gupta, "Coordination of Directional Relays Without using Topological Analysis of Power Transmission Systems," IE (I) Journal–Electrical, India, pp. 190–193, 1994.

[14] N. A. Laway, "Adaptive Optimal Coordination of Directional Overcurrent Relays of Large Scale Power Systems," Ph. D. Thesis, Department of Electrical Engineering, IIT Roorkee, 1994.

[15] H. H. Zeineldin, E. F. El–Saadany and M. M. A. Salama, "Optimal Coordination of Overcurrent Relays Using A Modified Particle Swarm Optimization, Electric Power Systems Research, Vol.–76, Issue–11, pp. 988–995, July 2006.

[16] A. J. Urdaneta, L. G. Perez and Harold Restrepo, "Optimal Coordination of Directional Overcurrent Relays Considering Dynamic Changes in the Network Topology," IEEE Transactions on Power Delivery, Vol.–12, No.–4, pp. 1458–1464, October 1997.

[17] L. G. Perez and A. J. Urdaneta, "Optimal Coordination of Directional Overcurrent Relays Considering Definite Time Back–up Relaying," IEEE Transactions on Power Delivery, Vol.–14, No.–4, pp. 1276–1284, October 1999.

[18] H. Zeienldin, E. F. El–Saadany and M. A. Salama, "Optimal Coordination of Directional Overcurrent Relay Coordination," IEEE Power Engineering Society General Meeting, pp. 1101-1106, 12–16 June, 2005.

[19] A. S. Braga and J. T. Saraiva, "Coordination of Directional Overcurrent Relays in Meshed Networks using Simplex Method," Proceedings, IEEE 8th Mediterranean MELECON Conference on Electro technical Conference, Vol.–3, pp. 1535–1538, 1996.

[20] H. A. Abyaneh and R. Keyhani, "Optimal Coordination of Overcurrent Relays in Power System by Dual Simplex Method," Proceedings, AUPEC Conference, Perth, Australia, Vol.–3, pp. 440–445, 1995.

[21] N. A. Laway and H. O. Gupta, "Adaptive Coordination of Directional Overcurrent Relays of Electrical Power Systems using Network Decomposition Approach," Journal of the Institution of Engineers (IEJ), India, Vol.–75, pp. 143–149, November 1995.

[22] H. A. Abyaneh, M. Al–Dabbagh, H. K. Karegar, S. H. H. Sadeghi and R. A. J. Khan, "A New Optimal Approach for Coordination of Overcurrent Relays in Interconnected Power Systems," IEEE Transactions on Power Delivery, Vol.–18, No.–2, pp. 430–435, April 2003.

[23] R. Ramaswami, M. J. Damborg and S. S. Venkata, "Coordination of Directional Overcurrent Relays in Transmission Systems – A Subsystem Approach," IEEE Transactions on Power Delivery, Vol.–5, No.–1, pp. 64–71, January 1990.

[24] N. A. Laway and H. O. Gupta, "Coordination of Directional Relays for Large Interconnected Power Systems using Local Optimization," IE (I) Journal–Electrical, India, pp. 109–112, 1998.

[25] C. W. So and K. K. Li, "Overcurrent Relay Coordination by Evolutionary Programming," Electric Power Systems Research, Vol.–53, Issue–2, pp. 83–90, February 2000.

[26] C. W. So and K. K. Li, "Time Coordination Method for Power System Protection by Evolutionary Algorithm," IEEE Transactions on Industry Applications, Vol.–36, No.–5, pp. 1235–1240, September–October 2000.

[27] C. W. So, K. K. Li, K. T. Lai and K. Y. Fung, "Application of Genetic Algorithm for Overcurrent Relay Coordination," IEE Proceedings, 6th International Conference (IEE) on Developments in Power System Protection, Conference Publication No. 434, Nottingham, U.K, pp. 66–69, 25–27 March, 1997.

[28] D. Birla, R. P. Maheshwari, H. O. Gupta, K. Deep and M. Thakur, "Application of Random Search Technique in Directional Overcurrent Relay Coordination", International Journal of Emerging Electric Power Systems, Vol.-7, Issue-1, September 2006.

[29] K. Deep , D. Birla, R. P. Maheshwari, H. O. Gupta, and M. Thakur, "A population Based Heuristic Algorithm for Optimizing Relay Operating Times", World Journal of Modelling and Simulation, Vol.-2, No-3, August 2006.

[30] J.J. Grainger, W.D. Stevenson Jr, "Power System Analysis," Tata McGraw–Hill Publishing Company Limited, New Delhi, 2003.

[31] H. Saadat, "Power System Analysis," Tata McGraw–Hill Publishing Company Limited, New Delhi, 1999.

[32] S.S. Rao, "Engineering Optimization: Theory and Practice," New Age International (P) Limited, 2002.

[33] G. C. Onwubolu, and B. V. Babu, "New Optimization Techniques in Engineering," (Eds.) and, Berlin, Springer, 2004.

[34] Kalyanmoy Deb, "Optimization for Engineering Design Algorithms and examples", PHI, New Delhi 2004.

[35] D. Karaboga and S. Okdem, "A Simple and Global Optimization Algorithm for Engineering Problems: Differential Evolution Algorithm", Turkey Journal of Electrical Engineering, Vol.-12, No-2, 2004.

[36] J. Brest, S. Greiner, B. Boskovic, M. Mernik and V. Zumer, "Self-Adapting Control Parameters in Differential Evolution: A Comparitive Study on Numerical Benchmark Problems", IEEE Transactions on Evolutionary Computation, Vol.–10, pp. 646–657, December 2006.

[37] J. Vesterstroem and R. Thomsen, "A comparative study of differential evolution, particle swarm optimization, and evolutionary algorithms on numerical benchmark problems," in Proc. IEEE Congr. EvolutionaryComputation, Portland, OR, Jun. 20–23, 2004, pp. 1980–1987.

[38] R. Storn and K. Price, Differential Evolution—A Simple and efficient adaptive scheme for global optimization over continuous spaces, Berkeley, CA, Tech. Rep. TR-95-012, 1995 [Online]. Available: citeseer.ist.psu.edu/article/storn95differential.html.

[39] R. Gämperle, S. D. Müller, and P. Koumoutsakos, "A parameter study for differential evolution," WSEAS NNA-FSFS-EC 2002. Interlaken,Switzerland, WSEAS, Feb. 11–15, 2002 [Online]. Available: http://www.worldses.org/online/

[40] V. Feoktistov and S. Janaqi, "Generalization of the Strategies in Differential Evolution," in Proc. 18th International Parallel and Distributed Processing Symposium (IPDPS'04), Apr. 26–30, 2004, pp. 165–170.

[41] J. Lampinen and I.Zelinka "Mixed Integer-Discrete-Continuous Optimization By Differential Evolution, Part 1: the optimization method," Proceedings of MENDEL'99, 5th International Mendel Conference on Soft Computing, June 9.–12. 1999, [Online]. Available: http://www.lut.fi/~jlampine/MEND99p1.ps/

[42] J. Lampinen and I.Zelinka "Mixed Integer-Discrete-Continuous Optimization By Differential Evolution, Part 2: a practical example," Proceedings of MENDEL'99, 5th International Mendel Conference on Soft Computing, June 9.–12. 1999, [Online]. Available: http://www.lut.fi/~jlampine/MEND99p2.ps/

[43] Z.Y. Dong, M. Lu, Z. Lu, and K.P. Wong, "A differential evolution based method for power system planning," in Proc. IEEE Congr. EvolutionaryComputation, Vancouver, Canada, July. 16–21, 2006, pp. 2699–2706.

[44] Y. Wallach, "Calculations and Programs for Power System Networks," Prentice–Hall Inc. Englewood Cliffs, ISBN 0–13–110321–0, New Jersey, 1986.

[45] J. A. Juves, R. W. Johnson, E. J. Mayer and S. S. Waters, "The Concept of Figure of Merit Applied to Power System Coordination," IEEE Transactions on Power Delivery, Vol. PWRD–1, No.–4, pp. 31–40, October 1986.

[46] M. J. Damborg, R. Ramaswami, S. S. Venkata and J. M. Postforoosh, "Computer Aided Transmission Protective System Design, Part – II, Implementation and Results," IEEE Transactions on Power Apparatus and Systems, Vol. PAS–103, No.–1, pp. 60–65, January 1984.

[47] N. A. Laway and H. O. Gupta, "Reduction of sympathy tripping using adaptive coordination," International conference on computer applications in electrical engg, Indian Institute of Technology, Roorkee, India, September 8-11, 1997.

[48] IEEE Power System Relaying Committee Report, "Distribution Line Protection Practices Industry Survey Results," IEEE Transactions on Power Delivery, Vol.–10, No.–1, pp. 173–186, January 1995.

[49] A. G. Phadke and S. H. Horowitz, "Adaptive relaying," IEEE Computer Applications in Power, vol. 3, no. 3, pp. 47–51, July 1990.

[50] T. Johannesson, F. Ross and S. Lindhal, "Reliability of Protection Schemes-Operational Experience 1976-2002," Proceedings of eight IEE conference on developments in power system protection, April 5-8, 2004.

[51] D. Birla, R. P. Maheshwari and H. O. Gupta, "An Approach to Tackle of Sympathy Trips in Directional Overcurrent Relay Coordination," IEEE Transactions on Power Delivery, Vol.–22, No.–2, pp. 851–858, April 2007.

[52] S.Tamrounglak, S.H.Horowitz, A.G.Phadke and J.S.Thorp, "Anatomy of power system blackouts: preventive relaying strategies," IEEE Transactions on Power Delivery, Vol.–11, No.–2, pp. 708–715, April 1996.

[53] J. A. Juves, R. W. Johnson, E. J. Mayer and S. S. Waters, "The Concept of Figure of Merit Applied to Power System Coordination," IEEE Transactions on Power Delivery, Vol. PWRD–1, No.–4, pp. 31–40, October 1986.

APPENDIX A

DATA FOR SAMPLE 6-BUS SYSTEM

A sample 6-bus system of the system taken from [31] on a 100MVA base, is given in Fig. A.1. Bus codes are: 1 slack bus; 2 generator bus; 0 load bus. The bus data and line data are mentioned in Tables A.1 and A.2, respectively.

Table A.1:Bus data for sample 6-bus test system (Fig. A.1)

Bus no.	Bus code	Voltage magnitude (p.u.)	Angle degree	Load		Generation		Injected Mvar (p.u.)
				MW	Mvar	MW	Mvar	
1	1	1.060	0.000	0.000	0.000	105.287	107.335	0.000
2	2	1.040	1.470	0.000	0.000	150.000	99.771	0.000
3	2	1.030	0.800	0.000	0.000	100.000	35.670	0.000
4	0	1.008	-1.401	100.000	70.000	0.000	0.000	0.000
5	0	1.016	-1.499	90.000	30.000	0.000	0.000	0.000
6	0	0.941	-5.607	160.000	110.000	0.000	0.000	0.000

Table A.2:Line data for the sample 6-bus test system (Fig. A.1)

Line no.	From bus	To bus	Line parameters (p.u.)		
			Resistance (R)	Reactance (X)	Half line charging (B/2)
1	1	4	0.035	0.225	0.0065
2	1	5	0.025	0.105	0.0045
3	1	6	0.040	0.215	0.0055
4	2	4	0.000	0.035	0.0000
5	3	5	0.000	0.042	0.0000
6	4	6	0.028	0.125	0.0035
7	5	6	0.026	0.175	0.0300

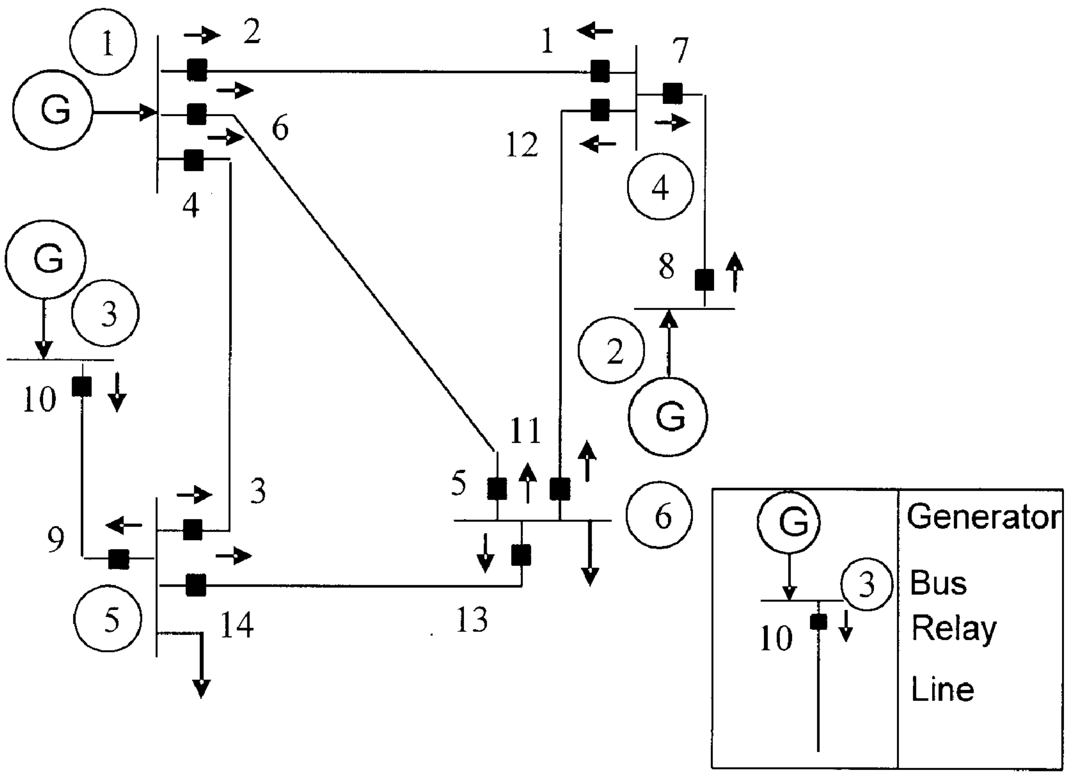

Fig. A.1. Single-line diagram of sample 6-bus system

APPENDIX B

DATA FOR IEEE-14 BUS SYSTEM

The IEEE 14-bus system is given in Fig. B.1. System data is taken from [44] on a 100MVA base. System diagram is taken from [44]. Bus codes are: 1 slack bus; 2 generator bus; 0 load bus. The bus data and line data are mentioned in Tables B.1 and B.2, respectively.

Table B.1:Bus data for IEEE 14-bus test system (Fig. B.1)

Bus no.	Bus code	Voltage magnitude (p.u.)	Angle degree	Load		Generation		Injected Mvar (p.u.)
				MW	Mvar	MW	Mvar	
1	1	1.060	0.000	0.000	0.000	232.064	-23.217	0.000
2	2	1.045	-4.971	21.700	12.700	40.000	32.129	0.000
3	2	1.010	-12.698	94.200	19.000	0.000	21.130	0.000
4	0	1.019	-10.315	47.800	-3.900	0.000	0.000	0.000
5	0	1.022	-8.790	7.600	1.600	0.000	0.000	0.000
6	2	1.070	-14.228	11.200	7.500	0.000	12.207	0.000
7	0	1.061	-13.346	0.000	0.000	0.000	0.000	0.000
8	2	1.090	-13.346	0.000	0.000	0.000	17.744	0.000
9	0	1.055	-14.924	29.500	16.600	0.000	0.000	0.190
10	0	1.050	-15.086	9.000	5.800	0.000	0.000	0.000
11	0	1.056	-14.788	3.500	1.800	0.000	0.000	0.000
12	0	1.055	-15.081	6.100	1.600	0.000	0.000	0.000
13	0	1.050	-15.160	13.500	5.800	0.000	0.000	0.000
14	0	1.035	-16.029	14.900	5.000	0.000	0.000	0.000

Table B.2:Line data for IEEE 14-bus test system (Fig. B.1)

Line no.	From bus	To bus	Line parameters (p.u.)		
			Resistance (R)	Reactance (X)	Half line charging (B/2)
1	1	2	0.01938	0.05917	0.0264
2	1	5	0.05403	0.22304	0.0246
3	2	3	0.04699	0.19797	0.0219
4	2	4	0.05811	0.17632	0.0187
5	2	5	0.05695	0.17388	0.0170
6	3	4	0.06701	0.17103	0.0173
7	4	5	0.01335	0.04211	0.0064
8	4	7	0.00000	0.20912	0.0000
9	4	9	0.00000	0.55618	0.0000
10	5	6	0.00000	0.25202	0.0000
11	9	10	0.03181	0.08450	0.0000
12	6	11	0.09498	0.19890	0.0000
13	6	12	0.12291	0.25581	0.0000
14	6	13	0.06615	0.13027	0.0000
15	7	8	0.00000	0.17615	0.0000
16	7	9	0.00000	0.11001	0.0000
17	9	14	0.12711	0.27038	0.0000
18	10	11	0.08205	0.19207	0.0000
19	12	13	0.22092	0.19988	0.0000
20	13	14	0.17093	0.34802	0.0000

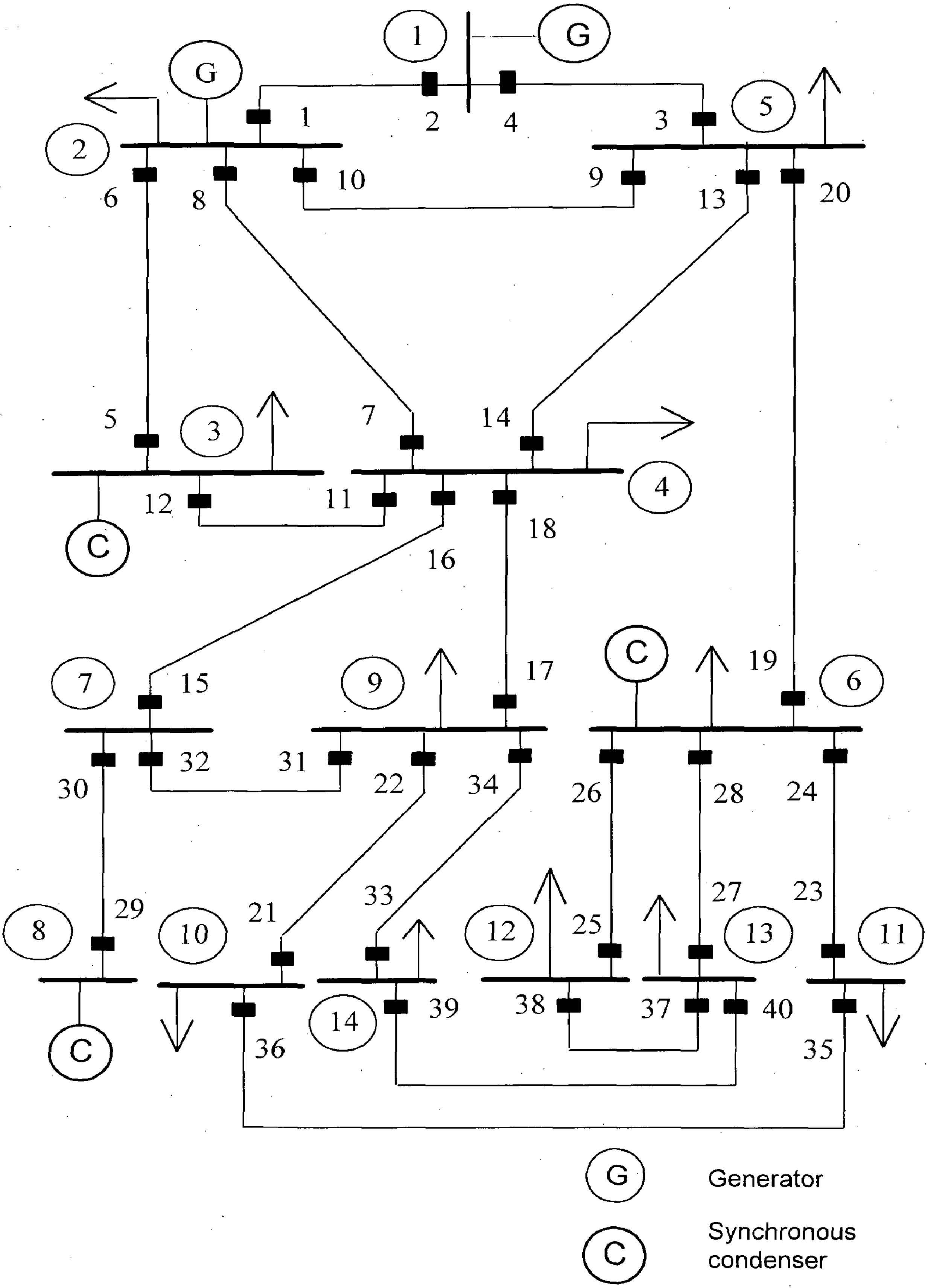

Fig. B.1. Single-line diagram of IEEE 14-bus system

APPENDIX C

DATA FOR IEEE-30 BUS SYSTEM

The IEEE 30-bus system is shown in Fig. C.1. The system data is taken from [44] on a 100MVA base. Bus codes are: 1 slack bus; 2 generator bus; 0 load bus. The bus data and line data are mentioned in Tables C.1 and C.2, respectively.

Table C.1. Bus data for IEEE 30-bus test system (Fig. C.1)

Bus no.	Bus code	Voltage magnitude (p.u.)	Angle degree	Load		Generation		Injected Mvar (p.u.)
				MW	Mvar	MW	Mvar	
1	1	1.060	0.000	0.000	0.000	260.950	-17.010	0.000
2	2	1.043	-5.496	21.700	12.700	40.000	48.826	0.000
3	0	1.022	-8.002	2.400	1.200	0.000	0.000	0.000
4	0	1.013	-9.659	7.600	1.600	0.000	0.000	0.000
5	2	1.010	-14.380	94.200	19.000	0.000	35.995	0.000
6	0	1.012	-11.396	0.000	0.000	0.000	0.000	0.000
7	0	1.003	-13.149	22.800	10.90	0.000	0.000	0.000
8	2	1.010	-12.114	30.000	30.000	0.000	30.759	0.000
9	0	1.051	-14.432	0.000	0.000	0.000	0.000	0.000
10	0	1.044	-16.024	5.800	2.000	0.000	0.000	0.190
11	2	1.082	-14.432	0.000	0.000	0.000	16.113	0.000
12	0	1.057	-15.301	11.200	7.500	0.000	0.000	0.000
13	2	1.071	-15.300	0.000	0.000	0.000	10.406	0.000
14	0	1.043	-16.190	6.200	1.600	0.000	0.000	0.000
15	0	1.038	-16.276	8.200	2.500	0.000	0.000	0.000
16	0	1.045	-15.879	3.500	1.800	0.000	0.000	0.000
17	0	1.039	-16.187	9.000	5.800	0.000	0.000	0.000
18	0	1.028	-16.889	3.200	0.900	0.000	0.000	0.000
19	0	1.025	-17.049	9.500	3.400	0.000	0.000	0.000
20	0	1.029	-16.851	2.200	0.700	0.000	0.000	0.000
21	0	1.032	-16.468	17.500	11.200	0.000	0.000	0.000
22	0	1.033	-16.455	0.000	0.000	0.000	0.000	0.000
23	0	1.027	-16.660	3.200	1.600	0.000	0.000	0.000
24	0	1.022	-16.829	8.700	6.700	0.000	0.000	0.043
25	0	1.019	-16.423	0.000	0.000	0.000	0.000	0.000
26	0	1.001	-16.835	3.500	2.300	0.000	0.000	0.000
27	0	1.026	-15.913	0.000	0.000	0.000	0.000	0.000
28	0	1.011	-12.056	0.000	0.000	0.000	0.000	0.000
29	0	1.006	-17.133	2.400	0.900	0.000	0.000	0.000
30	0	0.994	-18.016	10.600	1.900	0.000	0.000	0.000

Table C.2. Line data for IEEE 30-bus test system (Fig. C.1)

Line no.	From bus	To bus	Line parameters (p.u.)		
			Resistance (R)	Reactance (X)	Half line charging (B/2)
1	1	2	0.0192	0.0575	0.0264
2	1	3	0.0452	0.1852	0.0204
3	2	4	0.0570	0.1737	0.0184
4	3	4	0.0132	0.0379	0.0042
5	2	5	0.0472	0.1983	0.0209
6	2	6	0.0581	0.1763	0.0187
7	4	6	0.0119	0.0414	0.0045
8	5	7	0.0460	0.1160	0.0102
9	6	7	0.0267	0.0820	0.0085
10	6	8	0.0120	0.0420	0.0045
11	6	9	0.0000	0.2080	0.0000
12	6	10	0.0000	0.5560	0.0000
13	9	11	0.0000	0.2080	0.0000
14	9	10	0.0000	0.1100	0.0000
15	4	12	0.0000	0.2560	0.0000
16	12	13	0.0000	0.1400	0.0000
17	12	14	0.1231	0.2559	0.0000
18	12	15	0.0662	0.1304	0.0000
19	12	16	0.0945	0.1987	0.0000
20	14	15	0.2210	0.1997	0.0000
21	16	17	0.0824	0.1923	0.0000
22	15	18	0.1073	0.2185	0.0000
23	18	19	0.0639	0.1292	0.0000
24	19	20	0.0340	0.0680	0.0000
25	10	20	0.0936	0.2090	0.0000
26	10	17	0.0324	0.0845	0.0000
27	10	21	0.0348	0.0749	0.0000
28	10	22	0.0727	0.1499	0.0000
29	21	22	0.0116	0.0236	0.0000
30	15	23	0.1000	0.2020	0.0000
31	22	24	0.1150	0.1790	0.0000
32	23	24	0.1320	0.2700	0.0000
33	24	25	0.1885	0.3292	0.0000
34	25	26	0.2544	0.3800	0.0000
35	25	27	0.1093	0.2087	0.0000
36	27	28	0.0000	0.3960	0.0000
37	27	29	0.2198	0.4153	0.0000
38	27	30	0.3202	0.6027	0.0000
39	29	30	0.2399	0.4533	0.0000
40	8	28	0.0636	0.2000	0.0214
41	6	28	0.0169	0.0599	0.0650

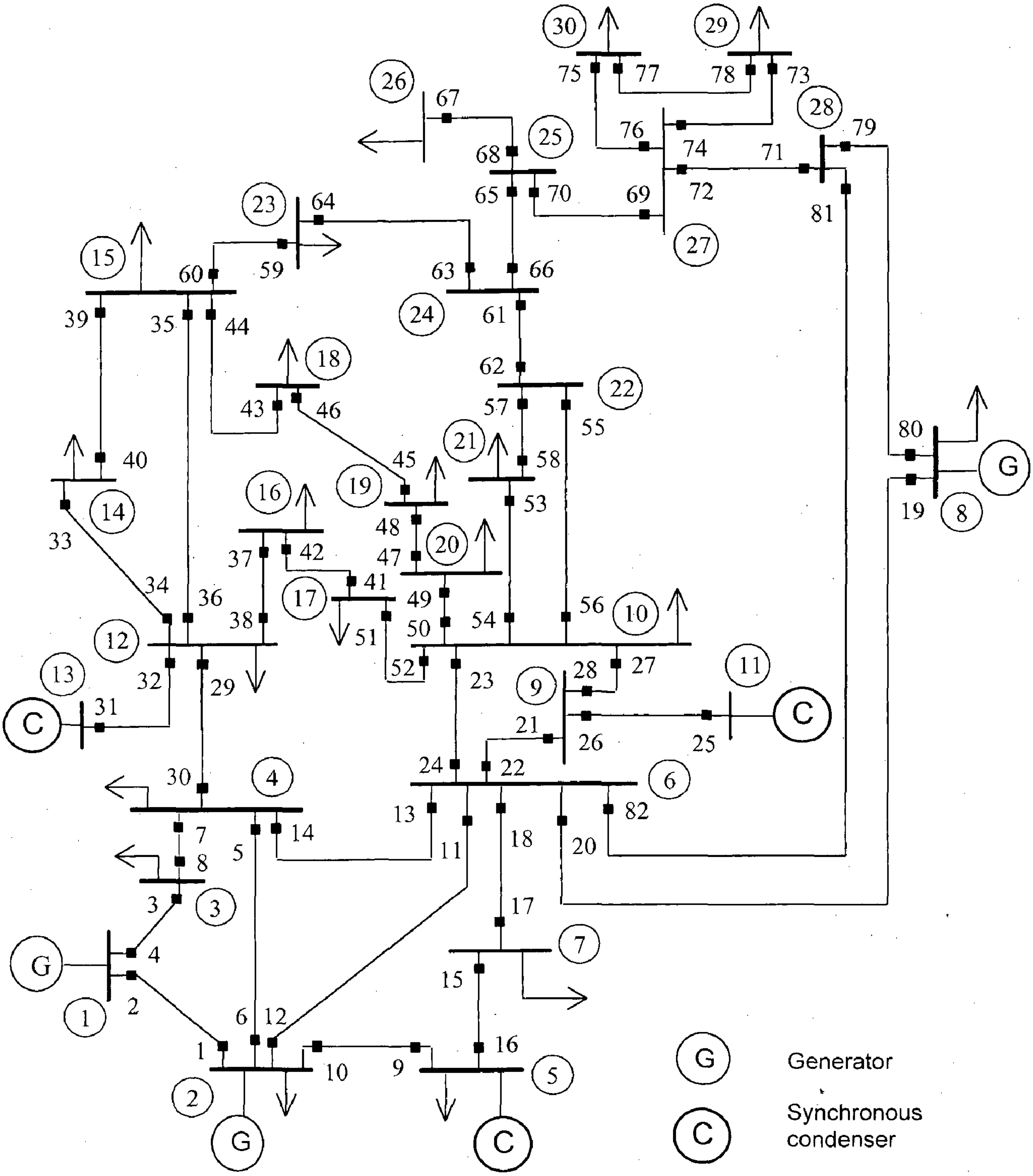

Fig. C.1. Single-line diagram of IEEE 30-bus system