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Optimal Sizing and Placement of FCL for Restoring Recloser-Fuse Coordination in DG-Integrated Distribution System Using MOPSO Algorithm

By

Purushottam Khadka

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **“Optimal Sizing and Placement of FCL for Restoring Recloser-Fuse Coordination in DG-Integrated Distribution System Using MOPSO Algorithm”** submitted by Purushottam Khadka in partial fulfilment of the requirements for the degree of Master of Science in Power System Engineering.

Prof. Dr. Nava Raj Karki
Supervisor & Program Coordinator
M.Sc. in Power System Engineering

Dr. Sujan Adhikari
External Examiner
Associate Professor
School of Engineering
Pokhara University

Mahammad Badrudoza
Associate Professor
Head of Department

ABSTRACT

With the demand for a more reliable power supply and the decentralization of the power system, there is a high penetration level of distributed generators in the distribution system. Some merits of DG integration are power loss reduction, voltage profile improvement, reliability improvement, backup supply and so on. The high penetration level of DG in the distribution system has led to the large contribution of fault current by the DG units to the fault location. The problem with the fault current provided by the DG unit is that the proper coordination between protective devices such as recloser-fuse coordination is disturbed. To restore the protection coordination between recloser and fuse, the fault current needs to be reduced. The fault current can be reduced by using a fault current limiter. With the optimal planning of Fault Current Limiter (FCL), the protection-coordination between recloser-fuse can not only be maintained but also the cost associated with FCL installation can be reduced. This thesis is focused on minimizing the size and the number of FCL for maintaining recloser fuse coordination. Moreover, the FCL should also reduce the voltage sag in the distribution system during the fault condition. Because of the flow of large fault current, there is a large voltage drop along the distribution line which results in low bus voltage. Since FCL reduces the fault current, the optimal sizing and placement of FCL should also minimize the voltage sag. Thus, in this thesis, the four objective functions:- the reduction of the fault current through the protective device to restore recloser fuse coordination, the reduction of the size of FCL, the reduction of the number of FCL, and the reduction of voltage sag during fault conditions are considered. The optimization problem is solved by using the Multiple Objective Particle Swarm Optimization Method (MOPSO) which uses non dominated solutions found in the external repository to guide the flight of the particle in the search space. Unlike PSO which gives a single solution to the optimization problem, MOPSO provides a set of non-dominated solutions which are called Pareto optimal solutions. Out of many non-dominated solutions, the best solution for the optimization problem is the solution with the minimum number of FCL along with a minimum size that can restore the recloser fuse coordination as well as maintain the voltage sag during the fault condition.

The optimal calculation of size, number and placement of FCL are considered for two test systems: Canadian Bench Mark Test System, and IEEE 69 bus test system. The optimization problem using MOPSO has been solved in MATLAB and the results are simulated and verified in ETAP software. For the Canadian Bench Mark Test System, only two FCLs with a total size of 3.093 pu was found necessary. The current minimization and voltage minimization indexes were 8.867 pu and 0.530 pu respectively. Similarly, for IEEE 69 bus system, 12 FCLs with a total size of 1.978 pu was found necessary. The current minimization and voltage minimization indexes were 28.276 pu and 0.492 pu respectively.

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LIST OF ACRONYMS AND ABBREVIATIONS

DC	:	Direct Current
AC	:	Alternating Current
MATLAB	:	Matrix Laboratory
ETAP	:	Electrical Transient Analyzer Program
DG	:	Distributed Generation
PV		Photo Voltaic
FCL		Fault Current Limiter
PSO		Particle Swarm Optimization
NLP		Non-Linear Programming
EA		Evolutionary Algorithm
MOPSO		Multiple Objective Particle Swarm Optimization
IEEE		Institute of Electrical and Electronics Engineers

CHAPTER 1. INTRODUCTION

1.1 Background

The future of the electrical market belongs to the distributed generation. DG sources are clean, non-polluted and renewable forms of energy [1]. With the advent of power electronic devices and the decline in the price of DG sources (PV, Wind), the use of DG for power generation has increased significantly. As a result, the traditionally dominated centralized generation is now being replaced by a distributed generation where the DG power sources are directly integrated into the distribution system. Integration of DG power into the distribution system reduces the power loss, decreases voltage drop, improves bus voltage and provides backup in case the utility source fails [2]. However, the probability of failure of protection coordination is high in DG integrated distribution system specifically when the DG source is a synchronous generator [3].

Protection coordination is the process of selecting the appropriate setting of protective devices so that the protective devices in the power system are properly coordinated. The protection coordination aims to differentiate between temporary and permanent faults restoring the system as fast as possible in case of the interruption due to temporary faults and minimizing the interruption of electrical power to the least number of consumers in case of permanent faults [4]. The proper coordination between the protective devices is required for this purpose. In a power system, the protection coordination can be classified into breaker-recloser, recloser-fuse and fuse-fuse coordination. In this thesis, the protection coordination between recloser and fuse is discussed. The recloser is a protective device that breaks the circuit like a circuit breaker but closes automatically after a few seconds. The recloser is generally installed along the main feeder and has two operating modes- fast mode and slow mode, and the fuses are usually installed along the laterals of the main feeder and have two inverse time characteristics – melting and total clearing time characteristics that lie between the two operating modes of the recloser. Most of the faults that occur in the distribution system are temporary and occur for a short duration. If the fault occurs at any laterals which are tapped from the main feeder, the recloser fast mode interrupts the supply and again restores it after a few seconds. In case of a temporary fault, the fault has vanished and the supply of power is restored. For temporary faults lasting for a longer duration, the recloser takes few attempts to restore the power. For simplicity of analysis, it is considered that temporary fault lasts for a few seconds and one attempt of recloser is enough for clearing the temporary fault. In case the fault is permanent, when the recloser closes the circuit (only one reclosing attempt of recloser is considered), the lateral fuse operates to isolate the faulty section from the main feeder. Sometimes, the fuse fails to clear the permanent fault and, in that case, the slow operating mode of the recloser opens the circuit. Thus the proper coordination of protection devices requires the sequence of operation to be such that recloser fast mode should operate before fuse and fuse should operate before recloser slow mode.

The traditional distribution system is radial and there is a unidirectional flow of power from the nearby substation to the consumer premises. Without DG, the substation is the only supplier of fault current and the distribution system protection coordination (Recloser-Fuse coordination) is designed considering the fault fed by the substation only. With the integration of DG, the fault is fed by both substation and DG. The fault current depends upon the location, size and type of DG. Generally, synchronous DG units supply a large amount of fault current. When synchronous units are present in the distribution system, the fault MVA in the system also increases. Here, in this thesis work, synchronous DG units are considered for the analysis. The location of the DG unit from the fault point also plays a crucial factor in determining how much fault current a DG unit can contribute to the faulty section [5]. The integration of DG may cause the fault current in the fuses to exceed the fault current through recloser and the fuses may operate even for temporary fault. Thus, protection coordination is disturbed by the use of DG.

A fault current limiter (FCL) is a non-linear element that limits the fault current during fault occurrence without complete disconnection [6]. The special feature about FCL, unlike normal impedances, is that it has a very low impedance under normal system operating conditions, which means that the power flow and bus voltages are not affected in normal conditions, however, it presents a higher impedance at fault current levels reducing the fault current during a fault condition. When the fault occurs, the change in impedance from a very low value to a high value occurs rapidly even before the operation of a circuit breaker which can trip a circuit within a few milliseconds. Furthermore, after the clearance of fault and the return of the power system to the normal operating condition, the fault current limiter automatically restores its impedance to a very low value [7].

The problem of protection coordination in the DG integrated distribution system can be solved by using a fault current limiter which limits the fault current at a section to a value that is near to the system having no DG. The optimum implication of FCL depends upon its size and locations. The optimization of the size of FCL having a fixed location may prohibitively increase the size and cost of FCL. Thus, the economics of FCL suggests optimizing both size and location along with the restoration of recloser-fuse coordination. The cost can be significantly reduced when not only the size but also the number of FCL to be installed in the system is less. The high impedance of FCL during fault condition can be further exploited to minimize the voltage sag problem that occurs in buses other than the fault bus during the fault condition. Voltage sag occurs because a large fault current flows through the branches of the network which results in a large voltage drop in the branches. The main problem a voltage sag creates is that when a fault occurs at one section of the network, some loads may be lost in the healthy section before the clearance of the fault.

1.2 Problem Statement

For proper coordination of the protective device, the recloser should clear the temporary fault in fast mode, and if the fault persists in case of a permanent fault, the fuse must act. An example of mal-operation can be an operation of fuse before recloser in case of a temporary fault, and this is the most likely scenario in case of DG-integrated distribution system. The penetration of DG may cause the fault current flowing through the fuse to be greater than the fault current flowing through the recloser as the synchronous generator (DG) will also supply the fault current to the fault location. This may cause the fuse to operate before recloser fast mode even for temporary fault interrupting the supply for several hours for a fault that happens for a few seconds.

And another problem during fault condition is voltage sag in buses other than the fault bus during the fault condition. Voltage sag occurs because a large fault current flows through the branches of the network which results in a large voltage drop along the branches. The main problem a voltage sag creates is that when a fault occurs at one section of the network, some loads may be lost in the healthy section of the network before the clearance of the fault. After isolating the faulty section from the healthy section, the load may need to be switched on again. To maintain the load in healthy sections of the network during the fault, the voltage sag needs to be minimized.

Both the problem of recloser fuse miscoordination and voltage sag can be solved by using a fault current limiter. The Fault Current Limiter limits the fault current but a proper optimization scheme is required for maintaining recloser-fuse coordination which requires increasing the number and the size of FCL [8]. However, increasing the number and size increases the cost of the installation which may become prohibitively large. On the other hand, reducing the number and the size for reducing installation cost may not properly maintain recloser-fuse optimization. Furthermore, the optimal placement of FCL should also be kept in mind [9]. The appropriate location and minimum number of FCL should be selected that can restore recloser fuse coordination and minimize voltage sag. Thus, it is a multi-objective optimization problem involving contrasting requirements of simultaneous reducing the size of FCL, number of FCL, restoring recloser fuse coordination and minimizing voltage sag.

1.3 Objective and Scope

The objective of this thesis work is to optimize the size, the location and the number of Fault Current Limiters for restoring recloser-fuse coordination and minimizing voltage sag during a fault condition.

This thesis work focuses on optimizing fault current limiters in a distribution system. The optimal planning of FCLs reduces the increased value of fault current flowing through recloser and fuse after DG integration. If it were not for the fault current limiter, the capacity of the substation breaker would have to be upgraded by replacing the old breaker with the new breaker having higher capacity because the short circuit current after integration of the DG unit may exceed the rating of the breaker.

Moreover, after the integration of the DG unit, the relay settings of the protective devices should be changed for maintaining the system protection because of the new increased value of fault current. By optimal planning of FCL, the fault current can be reduced to the original value and the original settings of the relay can safely clear the system fault.

In addition to that, the main problem during the fault condition is the voltage sag which may cause unwanted tripping of the major loads of the healthy section. This problem could be mitigated by minimizing the voltage sag using the fault current limiter.

1.4 Report layout

This thesis has been organized into six chapters.

Chapter 1 gives a brief introduction regarding the implications of distributed generation in the distribution system, protection coordination which briefly describes recloser and fuse coordination, and the use of Fault Current Limiter to restore protection coordination.

Chapter 2 gives the overview of the literature review on the need for FCL in the distribution network, the impact of distributed generation on protection coordination, and various researches regarding optimum sizing and placement of Fault Current Limiter.

Chapter 3 gives the overview of the research methodology, the formulation of the optimization problem, the solution algorithm, and the algorithm implementation of MOPSO for calculating the optimum size, the position and the number of Fault Current Limiter.

Chapter 4 describes the system under consideration, introduces the MATLAB software for solving the optimization problem, and ETAP software for simulating the recloser fuse coordination.

Chapter 5 discusses simulation results, performs output analysis and verifies the result of MOPSO for restoring recloser fuse coordination in ETAP.

Chapter 6 presents the conclusion of this thesis work.

Finally, this thesis ends with a list of reference papers used for this thesis work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Today serious attention has been drawn towards the electricity market because of the increase in the price of natural gas and petroleum products along with environmental concerns shown by many countries imposing regulations to alleviate pollution levels. This has led to the emergence of distributed generation technology in the electrical industry. As more distributed generations are connected in the system, the network becomes more complex with the increase in the fault current in a network, and this current will exceed the maximum short-circuit capacity of transformers and protective devices. Thus, the protective devices such as circuit breaker need to be replaced with a new one having a larger breaking capacity to protect the electrical equipment.

An alternate option could be to use a fault current limiter to limit the fault which can be done by implementing various methods such as applying a series reactor, high impedance transformer, current-limiting fuses and solid-state devices. However, the major problem with these devices is that two or three fault current cycles are required before they get activated during which maximum prospective fault current gets bypassed by the limiter which decreases their operational functionality. Moreover, these devices increase power loss and voltage drop in the system during normal operating conditions [10].

Superconducting Fault Current Limiter (SFCLs) is one of the most prominent FCL devices that can reduce fault current within the first cycle of the occurrence of a fault. Another remarking feature of SFCL is that it does not create power loss and voltage drop problem during normal system operation as it has zero impedance under normal condition, but the impedance changes from zero to a large value in the event of the occurrence of a fault [11]. The fault current limiter has not only been used to minimize fault current to avoid replacement of circuit breaker with a higher breaking capacity but also to restore protection coordination between protective devices which gets disturbed after synchronizing DG units to the distribution system.

It has been observed that several methods have been proposed in the literature to maintain recloser and fuse coordination in the presence of the DG unit. In [3], the protection coordination is maintained by calculating the maximum size of DG that would not affect the coordination on a feeder. This method is not a viable solution as the maximum size of DG is based on other various important criteria such as load demand on the feeder, availability of renewable resources, technical, political, financial factors, and so on.

In [12], a microprocessor-based recloser was suggested to maintain protection coordination. It was concluded that a traditional recloser cannot meet the new protection requirements after the integration of DG in the distribution system, and hence suggested that a microprocessor-based recloser that can select the TCC characteristics providing a variety of curve choices from the memory to adjust itself to keep the protection coordination between recloser and fuse when the distributed generation is introduced in the system. A sensitivity analysis based on bus fault current reduction to reduce the search space in finding the candidate locations for FCL placement was suggested by [5] and even uses a genetic algorithm to solve the optimum FCL placement problem. However, the optimum sizing of FCL has not been discussed in this paper.

In [13], the optimal sizing of FCL is done using Particle Swarm Optimization (PSO) algorithm. This paper formulates the FCL sizing problem as an NLP problem that optimizes size to maintain fault current levels due to the addition of DG in a protective device close to the original values without DG. However, the results of this paper indicate that the large size of FCLs is required which are very expensive. The weakness of [13] is overcome by [2] which adds another objective function for minimizing the FCL size. Moreover, it further adds the next objective function to reduce the voltage sag problem during the fault condition. The optimization problem is solved by using the MOPSO algorithm. The result of this paper shows that a large number of FCLs are required which is not a viable solution and the paper fails to show how the protection coordination is restored by using FCL whose sizes are calculated by using MOPSO.

Thus, this thesis work tries to overcome the weaken ss of [2]. Here in this thesis, one more objective function which minimizes the total number of FCL is added, and the same MOPSO algorithm suggested by [2] is implemented. Moreover, the optimization results have been tested and verified in ETAP.

2.2 Permanent and Temporary Faults

Temporary faults are momentary faults that just occur for short time and vanishes automatically. Such faults occur when there is electrical contact between phase or ground contacts momentarily. This may be caused by lightning, flashover, high wind, tree leaves and branches momentarily touching the conductor etc. In overhead lines, approximately 75-90% of the total number of faults are temporary. These faults are usually cleared by auto-recloser. When temporary faults occur, the fault duration is minimized to avoid the tripping of the protective device requiring replacement (e.g. fuse) to avoid temporary fault from becoming permanent.

On the other hand, permanent faults occur for a longer duration, does not vanish automatically and requires repairs by a repair crew e.g. removing tree limbs, replacing punctured disc and pin insulators, replacing burnt conductors, blown fuses etc. Unlike temporary faults where the protection coordination aims to minimize fault duration, in permanent faults, it aims to minimize the number of customers affected. Generally, in a distribution system, permanent fault along the laterals are cleared by fuses at lateral tap points.

2.3 Protection Coordination

Protection Coordination is the process of selecting over current protection devices with certain time-current settings and their appropriate arrangement in series along with a distribution system. The protection coordination has main two aims:- to minimize fault duration during temporary fault and, to minimize the number of consumers affected during a permanent fault. The temporary fault should be cleared by the recloser within a few seconds of the initiation of the fault. If fast action is not taken, then the fault becomes permanent. There are various protective devices in the distribution system and these include fuse, relays, and recloser. Thus, protection coordination is required among fuse-fuse, recloser-fuse, relay-fuse and relay-recloser. Here, this thesis work is primarily focused on recloser-fuse protection coordination.

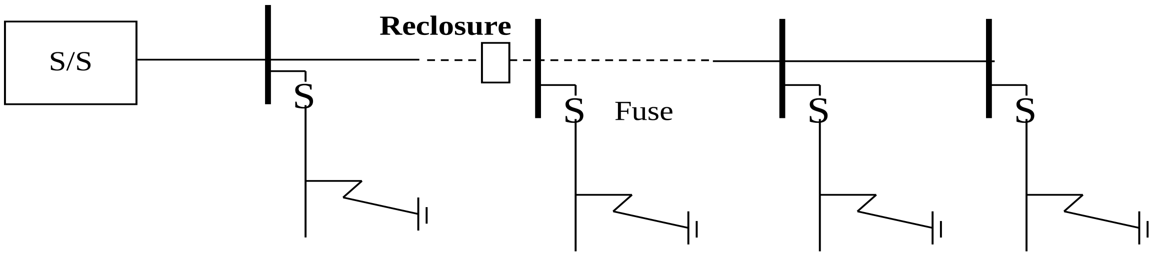

Figure 2.1 A distribution system showing protective devices: recloser and fuse [4]

Figure 2.1 shows the position of the recloser and fuse in the power distribution system. The reclosers are placed along the main feeder while the fuses are placed along the laterals. A recloser is a device that can interrupt fault currents which is very similar to that of a breaker but with the additional functionality of automatically closing the circuit in an attempt to re-energize a line. The recloser has two operating modes that utilize two inverse time curves:-Instantaneous (Fast mode) and Time delay (Slow mode) as shown in Figure 2.2. The recloser should trip within a few seconds for a temporary fault before the operation of a fuse, and then reclose the circuit automatically after a few seconds. The recloser makes few reclosing attempts depending upon the setting of the recloser before going on to a locked state after which it remains open until the operator comes and resets it. The fault is not cleared for the permanent fault. The recloser should not go to a locked (open) state for the permanent fault. Instead, if the fault is permanent, the fuse should blow after 1-2 reclosing attempts of a recloser. And the recloser should go into a locked state if the fuse fails to clear the permanent fault. This means that the delayed operation of a recloser should act as backup protection for the fuse in case of a permanent fault. Here, in this thesis, only one reclosing attempt of recloser is considered for simplicity.

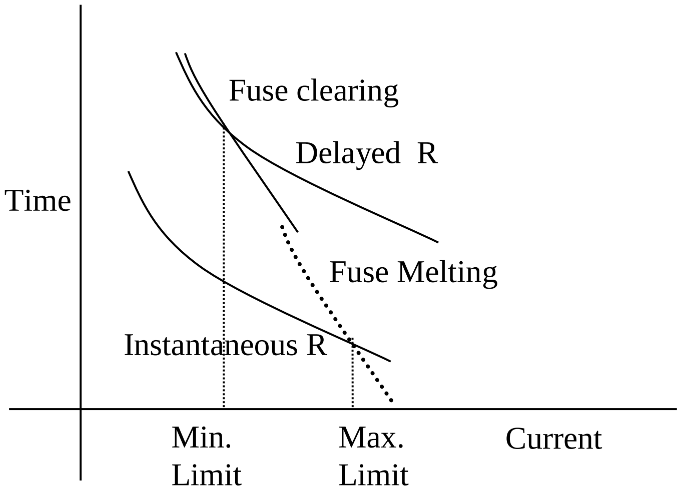

Figure 2.2 Inverse Time Current Characteristics of Recloser and Fuse [4]

The fuse has the melting and clearing time characteristics as shown in Figure 2.2. The melting time is the time that the fuse takes to start melting after the occurrence of a fault and the clearing time is the time taken by the fuse to clear the fault. The clearing time characteristics are above the melting time characteristics. The intersection of fuse and recloser TCC characteristics gives the minimum and maximum fault current. It is worth mentioning that to properly maintain power system protection coordination, the fault current in the system should lie between the min and max limit as shown in Figure 2.2. It should be noted that the proper co-ordination of protection devices requires the sequence of operation to be that the recloser fast mode should operate before the fuse and the fuse should operate before the recloser slow mode. If the fault current lies below the min limit, the recloser delayed mode operates before the fuse and the protection coordination fails for permanent fault. If the fault current lies above max limit, the fuse operates before recloser fast mode and the protection coordination fails for temporary fault.

2.4 Protection Coordination Maloperation

The penetration of DG into the distribution system will result in improper synchronization between the fuse and the recloser. To illustrate the problem, the distribution system in the absence and the presence of the DG set is considered as shown in Figure 2.3 and Figure 2.4 respectively. Without DG, if the fault occurs at location 'A", only the substation will be the supplier of fault current. The fault currents flowing through the fuse and recloser are equal. However, when DG set is integrated at bus 3 and the fault occurs at location 'A", both the substation and DG set will be the supplier of fault. The fault current flowing through is the sum of substation and DG currents and the fault current flowing through recloser is only the substation current. Thus, it can be seen that the fault current flowing through the recloser is greater than the fault current flowing through the fuse. Hence, the fuse may blow before the recloser fast mode operates, and if this happens, then the protection coordination fails for temporary fault.

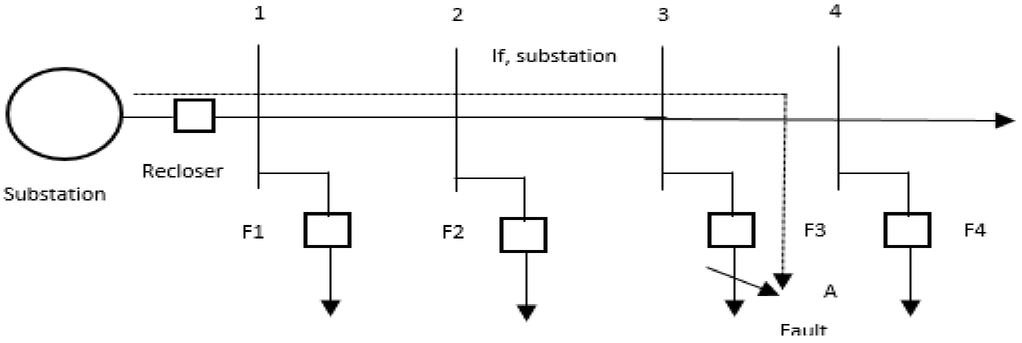

Figure 2.3 Distribution system without DG set

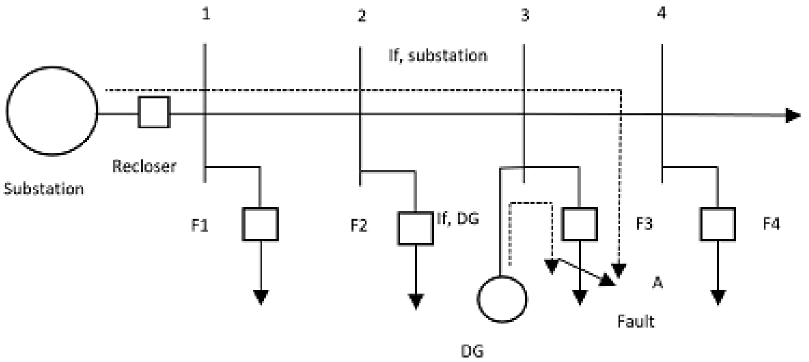

Figure 2.4 Distribution system with DG set connected to bus 3

2.5 Fault Current Limiter

Fault current limiter is a device that is used in a power system for reducing the fault current. As mentioned earlier, among various types of fault current limiters, Superconducting Fault Current Limiter (SFCLs) is one of the most prominent FCL devices that can reduce fault current within the first cycle of the occurrence of a fault. Another remarking feature of SFCL is that it does not create power loss and voltage drop problem during normal system operation as it has zero impedance under normal condition, but the impedance changes from zero to a large value in the event of the occurrence of a fault. The fault current limiter has not only been used to minimize fault current to avoid replacement of circuit breaker with a higher breaking capacity but also to restore protection coordination between protective devices which gets disturbed after synchronizing DG units to the distribution system. According to the characteristics of SFCL, there are resistive, inductive and commutated SFCLs. The quench and recovery characteristics of SFCL is given by Eq. 1.

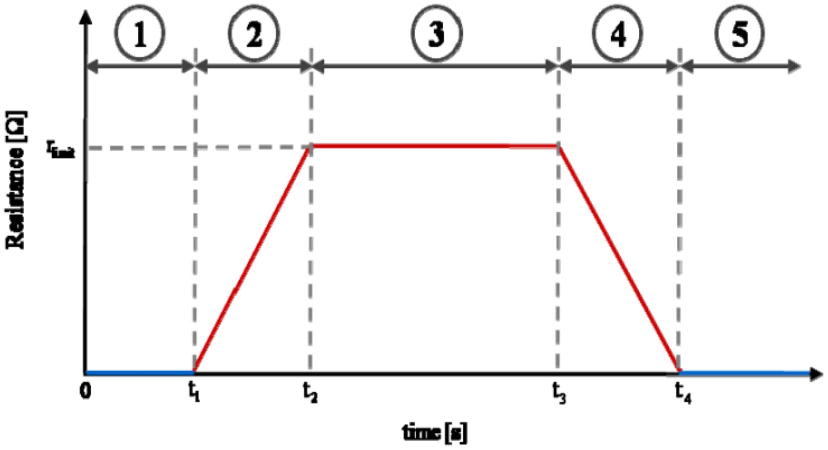

Figure 2.5 Resistance Characteristic of FCL [10]

$$f(t) = \begin{cases} 0 & t < t_1, t \geq t_4 \\ r_{limit}.(1 - e^{-k_2 t}) & t_1 \leq t \leq t_2 \\ rlimit & t_2 \leq t \leq t_3 \\ r_{limit}.e^{-k_2 t} & t_3 \leq t \leq t_4 \end{cases} \qquad \text{Eq. 1}$$

Figure 2.5 shows the resistance characteristics of the SFCL [10]. It can be seen that the resistance characteristics curve can be broken down into five sections. Section 1 (0 to t1) represents the normal operating condition during which the resistance of SFCL is zero. Section 2 (t1 to t2) represents quench characteristics. The resistance increases from zero to maximum during this time. The slope of the curve determines the quenching time. The less the quenching time, the faster the SFCL reaches the maximum resistance value. Section 3 (t2 to t3) shows that the resistance has increased to the maximum value and limits the fault current during a fault condition. Section 4 (t3 to t4) represents the recovery time after the clearance of fault current and flow of normal current. The less time for recovery means that the time taken to reconnect SFCL to a network is less after the flow of normal current in normal condition. Section 5 (t4 onwards) represents the condition after the system has fully returned to normal condition. Again, the resistance of SFCL during this condition is zero.

CHAPTER 3. METHODOLOGY

3.1 Methodology Approach

The methodology approach that has been adopted in this thesis is shown in Figure 3.1. To understand the past research work and historical development in the subject, a literature review is very essential. At first, the literature review on the advancement and development of FCL for limiting fault current and the study on recloser fuse coordination is done. Then the single-objective optimization problem is formulated and the optimum size of FCL is calculated using the PSO algorithm. Furthermore, multi-objective problems for four objectives are formulated and solved in MATLAB by using the MOPSO algorithm. Many non-dominated solutions are obtained and the selected solution based on the minimum value of each objective functions are analyzed. The final solution is chosen based on the minimum number and the size of FCL that can maintain protection coordination between recloser and fuse, and also minimize the voltage sag problem. After that, the system is simulated in ETAP [14] and the sequence of operation of the protective devices is observed for verification of protection coordination. Finally, the documentation is done.

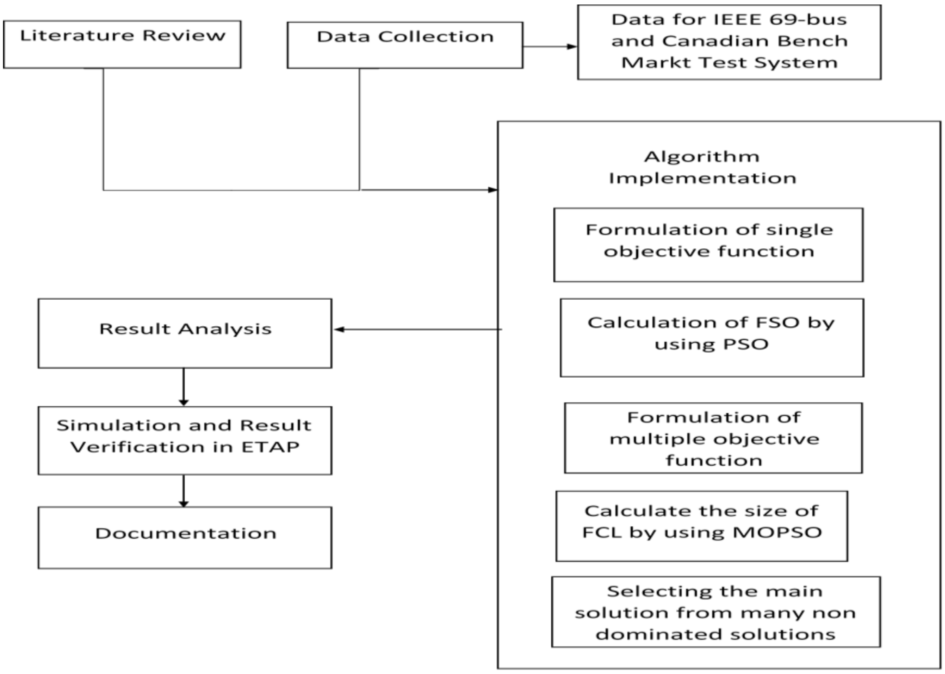

Figure 3.1 Methodology Approach

3.2 Formulation of Objective Function

The integration of DG into the distribution system disturbs protection coordination between recloser and fuse. To restore coordination, the fault current flowing in the system after DG integration must be made close to the value of the fault current that flows in the system without DG. Thus, the changes in fault current passing through fuses and main & backup protection of recloser must be minimized.

3.2.1 Single Objective Optimization Problem

First, the single objective optimization problem is solved by using the Particle Swarm Optimization Method in MATLAB before attempting to address the multiple objective optimization problems.

The single objective function is given in Eq. 1.

$$\text{Min } F_1 = \sum_{i=1}^{N} abs\left(I_{fuseBi} - I_{fuseAi}\right) + \sum_{m=1}^{M} abs\left(I_{rpBm} - IrpAm\right) + \sum_{n=1}^{N} abs(I_{rbBn} - I_{rbAn}) \qquad \text{Eq. 2}$$

Where,

- II_{fuseBi} and I_{fuseAi} are the fault currents flowing through i^{th} fuse due to fault downstream of the i^{th}fuse with FCL and without DG respectively.
- I_{rpBm} and I_{rpAm} represent the recloser primary protection current to nearby faults downstream the m^{th} recloser with FCL and without DG respectively.
- I_{rbBn} and I_{rbAn} present the recloser backup operation current for faults downstream of the n^{th} fuse with FCL and without DG respectively.

3.2.2 Multi-Objective Optimization Problem

The single objective optimization problem assumes the fixed location and number of FCL which may not be the optimum location and number. Thus, to optimize both location and number along with other objective functions, the multi-objective optimization problem is formulated.

Thus, the objective functions are expressed as:

$$Min\ F_1 = \sum_{i=1}^{N} abs\left(I_{fuseBi} - I_{fuseAi}\right) + \sum_{m=1}^{M} abs\left(I_{rpBm} - IrpAm\right) + \sum_{n=1}^{N} abs(I_{rbBn} - I_{rbAn}) \quad \text{Eq. 6}$$

$$Min\ F_2 = \sum_{k=1}^{L} (R_k + X_k) \quad \text{Eq. 5}$$

$$Min\ F_3 = \sum_{k=1}^{L} M_k\ for\ \ M_k = \begin{cases} 0 & if\ both\ R_k \text{ and } X_k \text{ are zeros} \\ 1 & otherwise \end{cases} \quad \text{Eq. 4}$$

$$Min\ F_4 = 1 - \frac{\sum_{i=1}^{M} \sum_{j=1}^{M} V_i^j}{M^2} \quad \text{Eq. 3}$$

Subject to,

$$R_{min} \leq R_k \leq R_{max}$$

$$X_{min} \leq X_k \leq X_{max}$$

$$I_{h,B} - I_{h,A} < €$$

Where,

- I_{fuseBi} and I_{fuseAi} are the fault currents flowing through i^{th} fuse due to fault downstream of the i^{th} fuse with FCL and without DG respectively.
- I_{rpBm} and I_{rpAm} represent the recloser primary protection current to nearby faults downstream the m^{th} recloser with FCL and without DG respectively.
- I_{rbBn} and I_{rbAn} present the recloser backup operation current for faults downstream of the n^{th}fuse with FCL and without DG respectively.
- R_k and X_k present the resistance and inductive reactance of the kth FCL
- R_{min} and R_{max} are lower and upper limits of R_i
- X_{min} and X_{max} are lower and upper limits of X_i
- M_k is an index that gives a value of 0 if both R_k and X_k are zeros, and 1 otherwise
- $I_{h,B}$ and $I_{h,A}$ are the current in the h^{th} feeder after and before DG connection
- N is the total number of fuses
- M is the total number of reclosers
- K is the total number of branches where FCL is installed

The first objective function minimizes the difference between the fault current flowing through the protective devices with FCL and without DG so that the fault current after the integration of DG is brought close to the value of fault current without DG to restore protection coordination. The second objective function minimizes the total size of FCL. The third objective function minimizes the number of FCL. The fourth objective function minimizes the voltage sag during the fault condition.

3.3 Optimization Techniques

To solve multi-objective optimization problems, numerous optimization techniques are available. However, Multi-Objective Particle Swarm Optimization is the methodology adopted in this thesis.

3.3.1 Particle Swarm Optimization

PSO is one of the most common nature-inspired evolutionary metaheuristic optimization algorithms [15]. It was created in 1995 by James Kennedy and Russell Eberhart. It is a robust stochastic optimization technique that is used to solve computationally hard optimization problems. This technique is based on the movement and intelligence of swarms such as birds, fish etc. In this optimization algorithm, a swarm of n particles communicate either directly or indirectly with one another using search directions and flying over a search space to locate a global optimum. Each particle updates its position according to its personal experience ($pbest$), overall experience ($gbest$) and the present motion of the particles [16]. In PSO, a particle is composed of three vectors: x-vector, p-vector and v-vector. The x-vector records the current position of the particle in the search space. The p-vector records the location of the best solution found so far by the particle i.e. ($pbest$). The v-vector contains a gradient for which the particle will travel if undisturbed.

$$v_{t+1} = W * v_t + c_1 * r_1 * (pbest - x_t) + c_2 * r_2 * (gbest - x_t) \qquad \text{Eq. 8}$$

$$x_{t+1} = x_t + v_{t+1} \qquad \text{Eq. 7}$$

Where,

- $pbest$ is the personal best of the individual
- $gbest$ is the global best of the particle
- c_1 and c_2 are acceleration coefficients
- w is the inertial weight
- $r_1 and$ r_2 are random numbers that lie between 0 and 1

The basic concept of PSO lies in accelerating each particle toward the best position found by it so far ($pbest$) and the global best position ($gbest$) obtained so far by any particle, with a random weighted acceleration at each time step. This is done by simply adding the v-vector to the x-vector to get another x vector as shown by Eq. 7

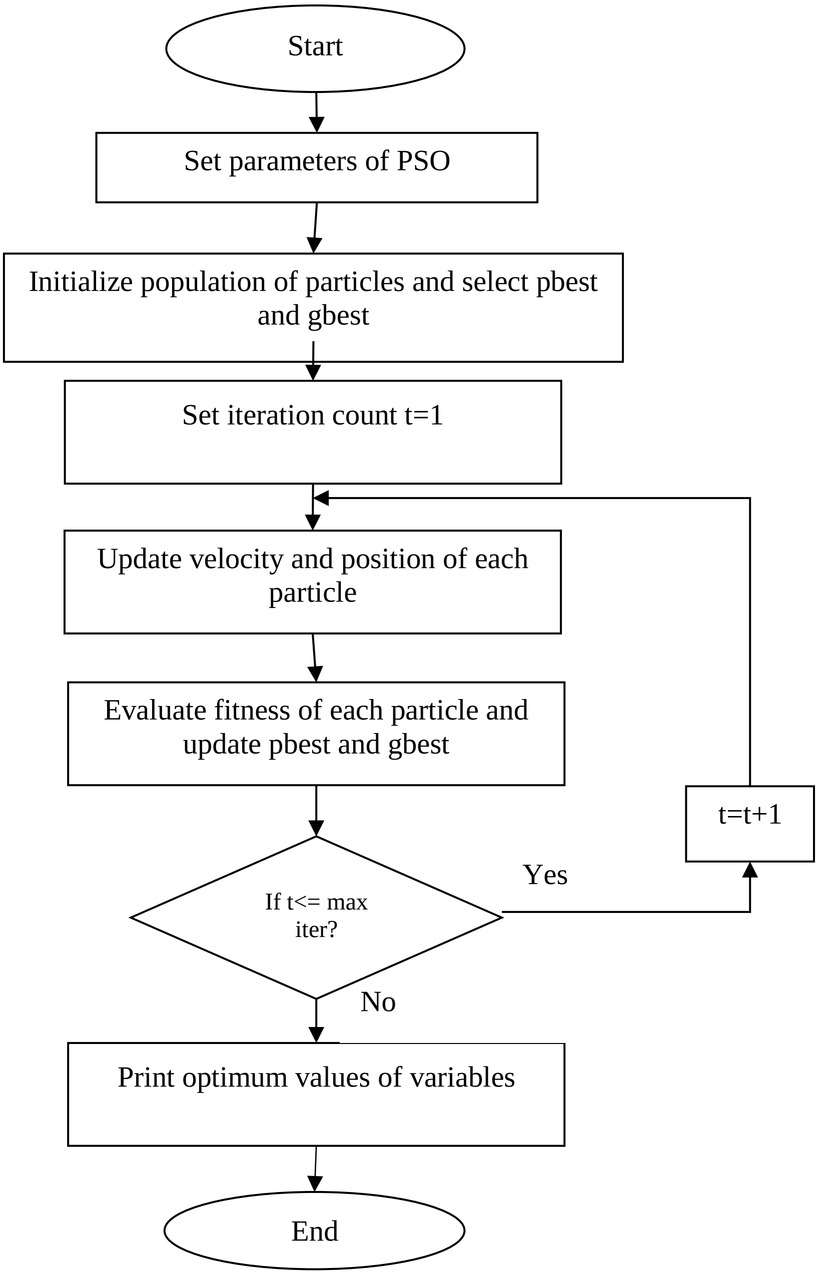

Figure 3.2 Flowchart of PSO

3.3.2 Multi-Objective Particle Swarm Optimization

MOPSO is an extension of Particle Swarm Optimization that solves optimization problems with multiple objectives [17]. The multi-objective optimization problem, unlike the single-objective optimization problem, does not provide a single solution but provides a set of non-dominated solutions which is called a Pareto optimal solution.

Some terminologies that are often used in multi-objective optimization problems are abstracted from [18] and defined below.

A solution x_1*is said to dominate the other solution* x_2*, if both the following conditions are true:*

1. *The solution* x_1 *is no worse than* x_2 *in all objectives when compared based on their objective function values.*
2. *The solution* x_1 *is strictly better than* x_2*in at least one objective.*

If the above conditions are satisfied, then x_1 is a non-dominated solution. The final solution set of non-dominated solutions are called Pareto optimal solutions.

Unlike PSO which uses global best for guiding the flight of every particle, MOPSO stores non-dominated solutions found in the current iteration to an external repository generates hypercubes of the search space explored so far and based on the roulette wheel selection method, a hypercube is selected which will guide the flight of the particle Hence, the MOPSO algorithm used in this thesis uses an external repository of particles to store the non-dominated solutions which are later used by other particles to guide their flight [19].

The flow chart of MOPSO is shown in Figure 3.3.

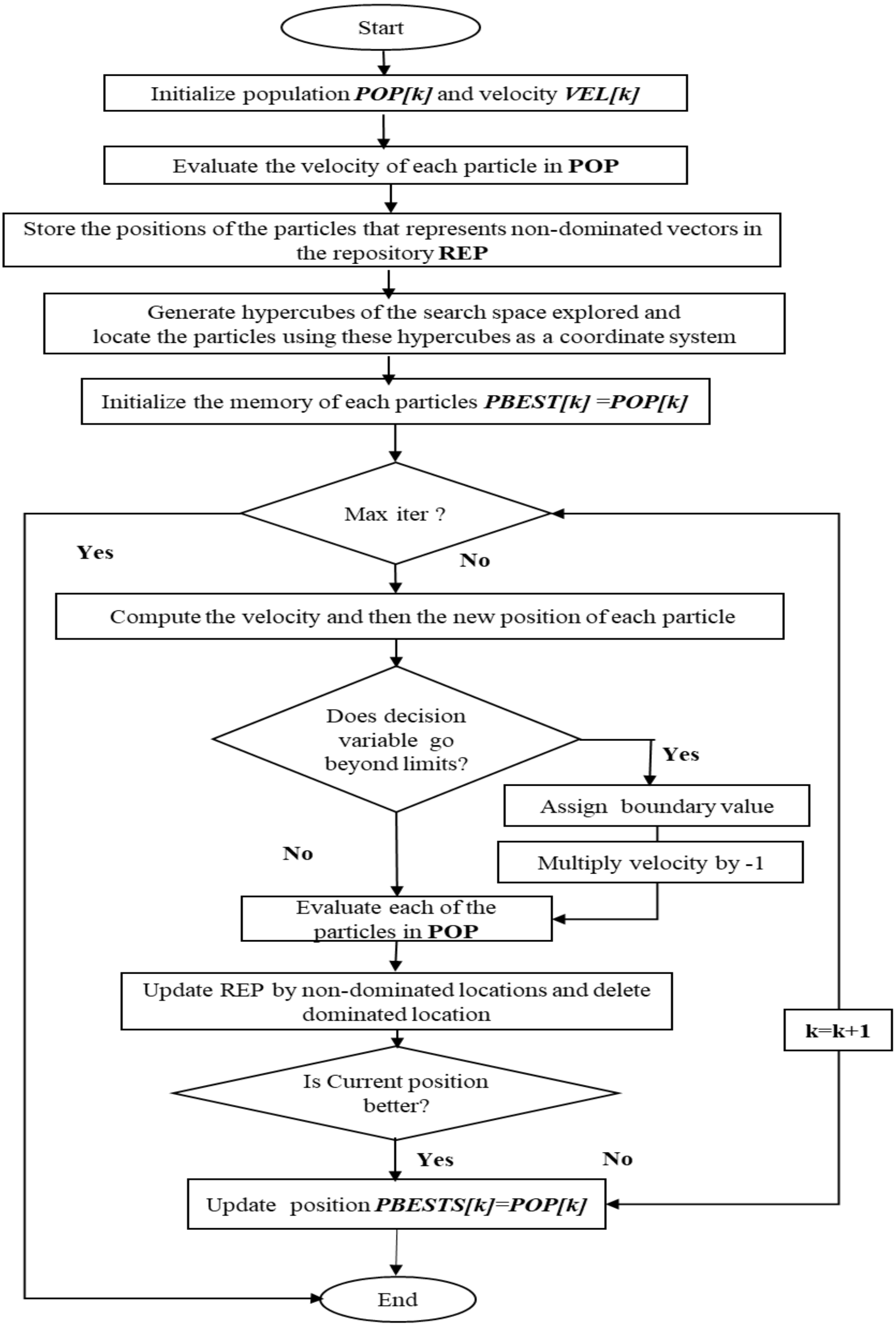

Figure 3.3 Flow Chart of MOPSO

3.3.2.1 MOPSO Algorithm for power system network

The MOPSO algorithm for solving the optimization problem for the power system network is given below.

1. Read the network parameters such as resistance, reactance and short circuit MVA
2. Locate the position of reclosers and fuses in the network
3. Create a function named *IwithoutDG* that finds and returns the fault current vectors I_{fuseA}, I_{rpA} and I_{rbA} which represents the fault current flowing through fuses, recloser primary protection and recloser backup protection respectively when DG is not connected to the network.
    a. Calculate the Z-impedance matrix from the network parameters
    b. Perform the short circuit analysis from the Z-impedance matrix to get the fault current
    c. For the fault at bus 'i', $\boldsymbol{I_{fuseA(i)}} = \frac{\boldsymbol{V_{prefault(i)}}}{\boldsymbol{Z(i,i)}}$, where $V_{prefault}$ represents the pre-fault voltage at the bus 'i' before the occurrence of a fault, and $Z(i,i)$ represents the element of Z impedance matrix with i^{th} row and i^{th} column
    d. For the m^{th} recloser primary protection current when the recloser is located between bus 'i' and bus 'j', $\boldsymbol{I_{rpA(m)}} = \frac{\boldsymbol{V_{(i,j)}}}{\boldsymbol{z(i,j)}}$ where, $V(i,j)$ represents the voltage at the bus 'i' when bus 'j' is faulted and $z(i,j)$ represents the branch impedance between bus 'i' and bus 'j'
    e. For the m^{th} recloser backup protection current when the recloser is located between bus 'i' and bus 'j' during fault at n^{th} bus, $\boldsymbol{I_{rbA(m,n)}} = \frac{\boldsymbol{V_{(i,n)}-V_{(j,n)}}}{\boldsymbol{z(i,j)}}$ where, $V(i,n)$ represents the voltage at the bus 'i' when bus 'n' is faulted, $V(j,n)$ represents the voltage at bus 'j' when bus 'n' is faulted and $z(i,j)$ represents branch impedance between bus 'i' and bus 'j'
4. Add DGs to the network

5. Initialize each particle in the population *POP*, where *POP* represents the FCL's resistance and reactance values

   For k=0 to MAX, where MAX= 2* (no of branches in the network + no of DG units)

   Initialize *POP [k]*

6. Create a function named *IandVwithDG* that takes the POP as an argument and returns the fault voltage sag index along with current vectors I_{fuseB}, I_{rpB} and I_{rbB} which represents the fault current flowing through fuses, recloser primary protection and recloser backup protection respectively when DG and FCL's are connected to the network.

   a. Calculate the Z-impedance matrix from the network parameters
   b. Perform the short circuit analysis from the Z-impedance matrix to get the fault current
   c. For the fault at bus 'i', $\boldsymbol{I_{fuseB(i)}} = \frac{\boldsymbol{V_{prefault(i)}}}{\boldsymbol{Z(i,i)}}$, where $V_{prefault}$ represents the pre-fault voltage at the bus 'i' before the occurrence of a fault, and $Z(i,i)$ represents the element of Z impedance matrix with i^{th} row and i^{th} column
   d. For the m^{th} recloser primary protection current when the recloser is located between bus 'i' and bus 'j', $\boldsymbol{I_{rpB(m)}} = \frac{\boldsymbol{V_{(i,j)}}}{\boldsymbol{z(i,j)}}$ where, $V(i,j)$ represents the voltage at the bus 'i' when bus 'j' is faulted and $z(i,j)$ represents the branch impedance between bus 'i' and bus 'j'
   e. For the m^{th} recloser backup protection current when the recloser is located between bus 'i' and bus 'j' when n^{th} fuse fails to clear the fault, $\boldsymbol{I_{rbB(m,n)}} = \frac{\boldsymbol{V_{(i,n)} - V_{(j,n)}}}{\boldsymbol{z(i,j)}}$ where, $V(i,n)$ represents the voltage at the bus 'i' during fault at bus 'n', $V(j,n)$ represents the voltage at bus 'j' when bus 'n' is faulted and $z(i,j)$ represents branch impedance between bus 'i' and bus 'j'
   f. Find the fault voltage at the bus 'i' when bus 'j' is faulted, $\boldsymbol{V_{(i,j)}} = \boldsymbol{V_{prefault(i)}} - \frac{\boldsymbol{Z(i,k)}}{\boldsymbol{Z(k,k)}} * \boldsymbol{V_{prefault(k)}}$, where $V_{prefault(i)}$ and $V_{prefault(k)}$ represents the voltage at the bus 'i' and 'k' respectively

```
        before the occurrence of a fault, $Z(i,k)$ represents the element of Z impedance matrix with $i^{th} row$ and $k^{th}$ column, $Z(k,k)$ represents the element of Z impedance matrix with $k^{th} row$ and $k^{th}$ column
    g.  Find the voltage sag index using $\boldsymbol{F_4 = 1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{M} V(i,j)}{M^2}}$ where, $V_{(i,j)}$ represents fault voltage at the bus 'i' when bus 'j' is faulted, and M is the total number of the bus in the system
7.  Initialize velocity VEL[k]
        For k=0 to MAX, where MAX= 2*(no of branches in the network + no of DG units)
        Initialize VEL [k]
8.  Evaluate each of the particles in POP and find the fitness function values
    a.  Call function IwithoutDG and IandVwithDG to calculate the fitness values using
            I.   $\boldsymbol{F_1 = \sum_{i=1}^{N} abs(I_{fuseBi} - I_{fuseAi}) + \sum_{m=1}^{M} abs(I_{rpBm} - IrpAm) + \sum_{n=1}^{N} abs(I_{rbBn} - I_{rbAn})}$
            II.  $\boldsymbol{F_2 = \sum_{k=1}^{MAX} POS(k)}$
            III. $\boldsymbol{F_3 = \sum_{k=1}^{MAX} M_k \; for \; M_k = \begin{cases} 0 & if\ k^{th}\ FCL\ has\ both\ R\ and\ X\ zeros \\ 1 & otherwise \end{cases}}$
            IV.  $\boldsymbol{F_4 = 1 - \frac{\sum_{i=1}^{M}\sum_{j=1}^{M} V(i,j)}{M^2}}$
9.  Initialize the best position of the particle and its fitness value
        FOR k=0 to MAX
            PBEST[k]=POS[k]
            PBEST_Fit[k] =POS_Fit[k]
10. Find the non-dominated particles and store the non-dominated particles in the repository REP
11. Generate the hypercubes of the search space explored so far, and locate the particles using these hypercubes as a coordinate system where each particle's coordinates are defined according to the values of its objective functions
12. WHILE the maximum number of generations has not been reached
    DO
```

a. Select leader REP[h] from the repository performing a roulette wheel selection based on the quality of each of the hypercube generated on step 11

b. Compute the velocity of each particle

$$VEL[k] = W\ x\ VEL[k] + R_1\ x\ (PBEST[k] - POP[k]) \\ + R_2 x(REP[h] - POP[k])$$

where W is the inertia weight; R_1 and R_2 are random numbers in the range [0…1], REP[h] is a value that is taken from the repository and represents the leader for the particular particle

c. Compute the new position of each particle adding the velocity produced from the previous step

$$POP[k] = POP[k] + VEL[k]$$

d. Perform mutation

e. Maintain the particles within the search space in case they go beyond the boundaries. When a decision variable goes beyond its boundaries, then the following actions are taken.

    I. The decision variable takes the value of its corresponding boundary (either the lower or the upper boundary)

    II. Its velocity is multiplied by (-1) so that it searches in the opposite direction

f. Evaluate each of the particles in POP as indicated by step 8

g. Update the particles in the repository by comparing the new particle fitness with the fitness of the particles already present in the repository. If the currently new non-dominated solution is dominated by any particle of the repository, the new particle is not allowed in the repository otherwise, the new particle enters the repository. Any dominated locations from the repository are eliminated in the process.

h. Update the best solution found so far when the current position of the particle is better than the position contained in its memory,

$$PBEST[k]=POS[k]$$

i. Update the generation

13. END WHILE

CHAPTER 4. SYSTEM UNDER CONSIDERATION, TOOLS AND SOFTWARE

4.1 System under Consideration

4.1.1 Canadian Bench Mark Test System

Canadian Bench Mark Test System is a simple 9 bus test system. The system consists of two feeders operating at a voltage level of 12.47 kV with an impedance of 0.1529+j0.4106 Ω/km. Each bus from bus 2 to bus 9 has a load of 2 MVA. There are two distributed generators DG1 and DG2 connected to bus 2 and bus 6 through transformer T1 and T2 respectively as shown in Figure 4.1 and the system parameters are shown in APPENDIX B. The rating of the generator used is 8MVA, 0.48kV. Since the load on all the buses are equal to 8MVA, the fuses are used with the rating of 100A.

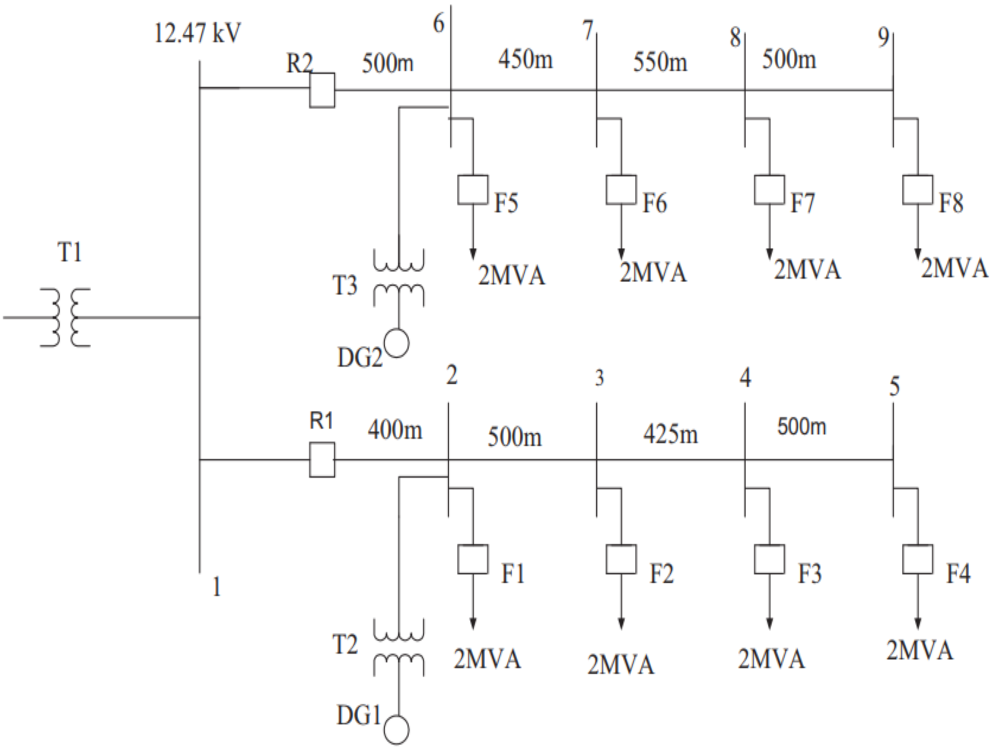

Figure 4.1 Canadian Bench Mark Test System

4.1.2 IEEE 69 bus test system

IEEE 69 bus test system is a radial distribution system that consists of 69 buses as shown in Figure 4.2. The data for this test system is given in APPENDIX A [20]. The system has a voltage rating of 12.7 kV. The data for fault current analysis is not available in the IEEE 69 bus system. Thus, some values for the system parameters are assumed. The substation is assumed to have a short circuit MVA of 50 MVA with an X/R ratio of 6. Four distributed generators are connected at buses 20, 32, 59 and 40 respectively as shown in Table 4.2. Each DG has a rating of 500kVA with a sub transient reactance of 5% at its base. Here, in this thesis, for protection coordination, seven reclosers from R1 to R7 are considered as shown in Figure 2.1. The position of reclosers are shown in Table 4.1

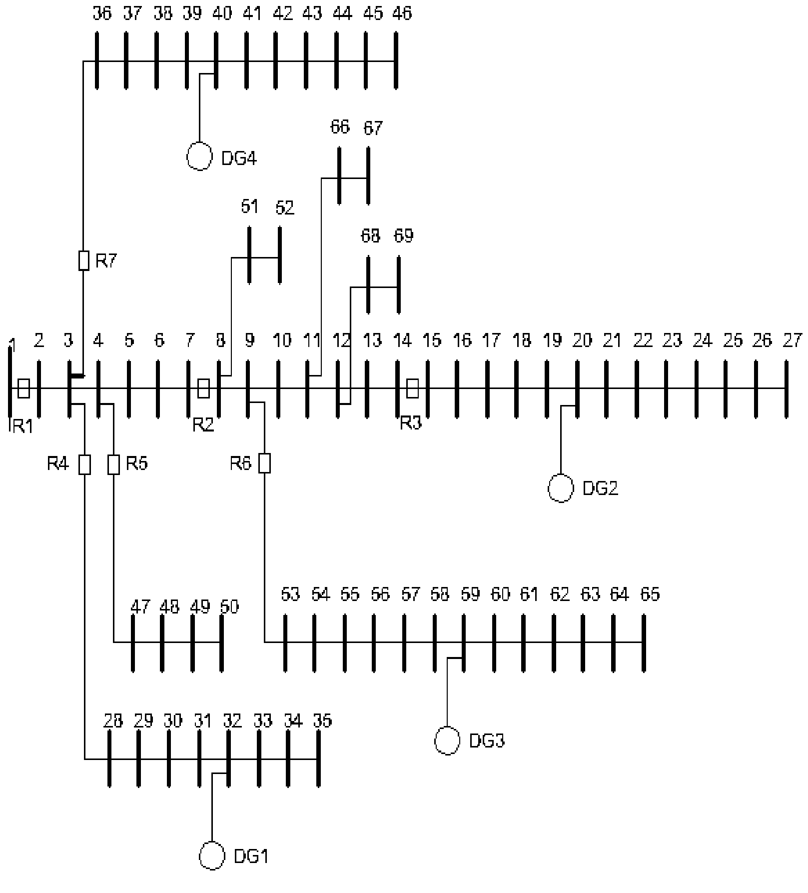

Figure 4.2 IEEE 69 test bus system

Table 4.1 Position of recloser in IEEE 69 bus system

Recloser	**Positions**
R1	Bus 1- Bus 2
R2	Bus 7- Bus 8
R3	Bus 14- Bus 15
R4	Bus 3- Bus 28
R5	Bus 4- Bus 47
R6	Bus 9- Bus 53
R7	Bus 3- Bus 36

Table 4.2 Position of DG in IEEE 69 bus system

DG unit	**Position**
DG1	Bus 20
DG2	Bus 32
DG3	Bus 59
DG4	Bus 40

4.2 Tools and Software

The technological advancement in computer architecture, software and programming tools have made the modelling and analysis of power system easy. In the past, the modelling and analysis were difficult, time-consuming and inaccurate. Many software tools use the mathematical model to simulate the performance of a power system to that of the real component. These mathematical models are integrated into a single module to simulate an actual power system. Two simulation software’s: MATLAB and ETAP have been used in this thesis for solving the optimization problem and simulating recloser fuse protection coordination respectively.

4.2.1 MATLAB

MATLAB stands for Matrix Laboratory. It is the user-friendly highly interactive programming tool developed by MathWorks which can be used for simulating a large number of engineering problems. In this thesis, MATLAB has been used for implementing MOPSO for solving the multi-objective optimization problem with four objectives for both Canadian Bench Mark Test System and IEEE 69 bus system.

Moreover, Matpower 7.0 package is also integrated with Matlab for simulating IEEE 69 bus system.

4.2.2 ETAP

ETAP refers to Electrical Transient Analyzer Program. It is a simulation software tool that can be used to model a power system and analyze its dynamics, transients and protection. In this thesis, ETAP Star – Protection and Coordination has been used to generate the TCC characteristics of Recloser and Fuse, and also to study the sequence of operation of protective devices during a fault condition.

CHAPTER 5. SIMULATION RESULTS AND DISCUSSIONS

At first, the optimal sizing of FCL for restoring recloser fuse coordination is done by using PSO considering minimization of fault current flowing through fuses and recloser as the single objective problem. Then, the multiple objectives will be introduced which will be solved by using MOPSO.

5.1 Canadian Bench Mark Test System

5.1.1 Single Objective Optimization Problem

The single objective optimization problem is solved by using Particle Swarm Optimization. At first, the Z-impedance matrix was computed using the Z-bus building algorithm from the system data, and then the fault analysis was performed to find the fault current through the recloser and fuse with and without DG in the network. The absolute value of the difference between the fault currents without DG and with DG & FCL is the objective function for the single objective optimization problem. After formulating the problem, the PSO algorithm was used to get the optimum size of FCL. Table 5.1 shows the fault current flowing through the fuses, recloser primary and backup protection without DG, with DG but no FCL and with FCL respectively. Here, IF1 to IF8 represent the fault current flowing through fuse 1 to fuse 8 respectively. IR1 (P) and IR2 (P) represent recloser primary protection current. IR1 (BF1) to IR1 (BF8) represent the recloser backup protection current when fuse 1 to fuse 8 fail to clear the fault respectively. It can be seen that with the integration of DG in the system, the fault currents through protective devices increase significantly.

Table 5.1 Fault current through protective devices in the single optimization problem

Device Fault Current	Without DG	With DG	With DG and FCL
IF1	1.3572	2.3676	1.4613
IF2	1.2692	2.111	1.3572
IF3	1.2005	1.9227	1.2769
IF4	1.1264	1.7328	1.1914
IF5	1.3388	2.3359	1.4413
IF6	1.2607	2.1073	1.3496

IF7	1.1736	1.8693	1.2485
IF8	1.102	1.6879	1.1664
IR1(P)	1.4327	1.9647	1.2887
IR2(P)	1.4327	1.9673	1.2887
IR1(BF1)	1.3572	1.8249	1.3588
IR1(BF2)	1.2692	1.627	1.2620
IR1(BF3)	1.2005	1.4819	1.1874
IR1(BF4)	1.1264	1.3356	1.1079
IR1(BF5)	1.3388	1.7938	1.2964
IR1(BF6)	1.2607	1.6183	1.2139
IR1(BF7)	1.1736	1.4355	1.1230
IR1(BF8)	1.102	1.2962	1.0492
FCL Source			**j0.0781**
FCL DG1			**5+j5**
FCLDG2			**j5**
Objective fun f1			**1.3511**
Objective fun f2			**15.0781**

FCLs are usually located at the places where the power element exits that can feed the fault. So, the FCLs can be placed at the source, DG1 and DG2 locations. When FCLs are integrated into the distribution system, the fault current decreases significantly. The optimum size of FCLs is found as:

DG1 FCL = 5+j5,

DG2 FCL = j5

Source FCL= j0.0781.

The value of the objective function is 1.3511 pu. The same value was obtained in [13].

5.1.2 Multiple Objective Optimization Problem

The problem with using PSO only for solving a single objective function is that the location and the number of FCL should be predefined which may not be the optimal number and location, and the size of FCL calculated is also large. In addition to that, the FCL may not decrease the voltage sag in buses other than the fault bus during a fault condition. Thus, considering the above-mentioned problems, three more additional objective functions are added which makes a minimization problem of four objective functions.

1) Minimization of the difference of fault current flowing through fuse, recloser primary and back up protection with FCL and without DG
2) Minimization of the size of FCL
3) Minimization of the number of FCL required
4) Minimization of voltage sag

Considering all of the above objective functions, the optimization problem is solved for the Canadian Bench Mark Test System. It is worthwhile mentioning that the optimization of multi-objective problem does not provide a single solution, rather provides a set of non-dominated Pareto optimal solutions. Here, in this thesis, a solution set of 200 non dominated Pareto optimal solutions is obtained which is shown in APPENDIX C.

Out of these 200 solutions, a thorough analysis of each of the solution is done considering four different cases considering each of the four objective functions as the main function respectively. Afterwards, a compromise solution which minimizes each of the objective function to an extent that is acceptable and meets the required target is chosen as the main solution for this thesis.

Case 1) Minimization of fault current (f1) as the main objective function

Case 2) Minimization of the size of FCL (f2) as the main objective function

Case 3) Minimization of the number of FCL (f3) as the main objective function

Case 4) Minimization of voltage sag (f4) as the main objective function

5.1.2.1 Minimization of fault current (f1) as the main objective function

When the minimization of fault current flowing through the fuse, recloser primary and backup protection (f1) is chosen as the main objective function, the values of the objective functions are shown in Table 5.2. In this case, the current minimization index is 4.033 pu, the size of FCL is 6.278 pu, the number of FCL is 10 and the voltage minimization index is 0.699 pu.

Table 5.2 Objective function values when f1 is the main objective function

Index	**f1**	**f2**	**f3**	**f4**
181	4.033	6.278	10	0.699

Table 5.3 shows the comparison of voltage sag minimization index values for three different cases. Without DG, the voltage sag has a maximum value of 0.8897 pu. After adding DG, the voltage sag decreases to 0.8246 pu. With the further addition of FCL, the voltage sag reduces to 0.6991 pu.

Table 5.3 Voltage sag minimization index values in various cases (f1)

Conditions	**f4**
Without DG	0.8897
With DG	0.82460
With FCL	0.6991

Table 5.4 shows the fault current flowing through various protective devices. It can be seen that when there is no DG, the fault current flowing through fuse 1 (IF1) is 1.3572 pu. After the integration of DG in the system, the fault current increases to 2.3676 pu. Finally, after adding FCL, the fault current decreases to 1.3383 pu. Thus, the fault current with FCL is maintained close to the value without DG.

Table 5.4 Fault current through protective devices (f1)

Device Fault Current	**Without DG**	**With DG**	**With FCL**
IF1	1.3572	2.3676	1.3383
IF2	1.2692	2.111	1.2528
IF3	1.2005	1.9227	1.1788

IF4	1.1264	1.7328	1.1016
IF5	1.3388	2.3359	1.2873
IF6	1.2607	2.1073	1.1719
IF7	1.1736	1.8693	1.0891
IF8	1.102	1.6879	1.0222
IR1(P)	1.4327	1.9647	1.2533
IR2(P)	1.4327	1.9673	1.2533
IR1(BF1)	1.3572	1.8249	1.1926
IR1(BF2)	1.2692	1.627	1.1163
IR1(BF3)	1.2005	1.4819	1.0504
IR1(BF4)	1.1264	1.3356	0.9816
IR1(BF5)	1.3388	1.7938	0.7466
IR1(BF6)	1.2607	1.6183	0.6797
IR1(BF7)	1.1736	1.4355	0.6317
IR1(BF8)	1.102	1.2962	0.5929

Table 5.5 shows the location and size of FCLs.for min f1. It can be seen that 10 FCL’s with a total size of 6.278 pu are required for making the current minimization index the lowest. The large size of FCL has a reactance of 5 pu placed in series with DG2. Thus, this solution cannot be the ultimate solution.

Table 5.5 FCL locations and size pu (f1)

`From bus	**To bus**	**Rpu**	**Xpu**
0	1	0.0000	0.1000
1	2	0.0000	0.1976
2	3	0.0000	0.0006
3	4	0.0000	0.0055
4	5	0.0217	0.0001
1	6	0.2003	0.5489
6	7	0.1158	0.0000
7	8	0.0000	0.0000
8	9	0.0000	0.0001
6	0	0.0877	0.0000
2	0	0.0000	5.0000

Table 5.6 shows the per-unit voltage during various fault conditions. The element with row B1 and column F9 has a value of 0.636 pu means that the per-unit voltage at bus 1 is 0.636 pu when the fault occurs at bus 9.

Table 5.6 Voltage pu during various fault conditions (f1)

Vfault	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
B1	0.000	0.283	0.335	0.381	0.435	0.481	0.567	0.606	0.636
B2	0.034	0.000	0.084	0.151	0.232	0.499	0.582	0.619	0.648
B3	0.034	0.000	0.000	0.071	0.158	0.499	0.582	0.619	0.648
B4	0.034	0.000	0.000	0.000	0.093	0.499	0.582	0.619	0.648
B5	0.034	0.000	0.000	0.000	0.000	0.499	0.582	0.619	0.648
B6	0.263	0.470	0.512	0.547	0.588	0.000	0.193	0.253	0.303
B7	0.263	0.470	0.512	0.547	0.588	0.000	0.000	0.080	0.143
B8	0.263	0.470	0.512	0.547	0.588	0.000	0.000	0.000	0.068
B9	0.263	0.470	0.512	0.547	0.588	0.000	0.000	0.000	0.000

5.1.2.2 Minimization of the size of FCL (f2) as the main objective function

When the minimization of the size of FCL (f2) is taken as the main objective function, the values of the objective functions are shown in Table 5.7. In this case, the current minimization index is 4.575 pu, the size of FCL is 1.692 pu, the number of FCL is 7 and the voltage minimization index is 0.610 pu.

Table 5.7 Objective function values when f2 is the main objective function

Index	**f1**	**f2**	**f3**	**f4**
166	4.575	1.692	7	0.610

Table 5.8 shows the fault current flowing through various protective devices. It can be seen that when there is no DG, the fault current flowing through fuse 1 (IF1) is 1.3572

pu. After the integration of DG in the system, the fault current increases to 2.3676 pu. Finally, after adding FCL, the fault current decreases to 1.3401 pu.

Table 5.8 Fault current through protective devices (f2)

Device Fault Current	Without DG	With DG	With FCL
IF1	1.3572	2.3676	1.3401
IF2	1.2692	2.111	1.2567
IF3	1.2005	1.9227	1.1908
IF4	1.1264	1.7328	1.1077
IF5	1.3388	2.3359	1.2852
IF6	1.2607	2.1073	1.2153
IF7	1.1736	1.8693	1.132
IF8	1.102	1.6879	1.0669
IR1(P)	1.4327	1.9647	1.4327
IR2(P)	1.4327	1.9673	1.4327
IR1(BF1)	1.3572	1.8249	0.8155
IR1(BF2)	1.2692	1.627	0.7648
IR1(BF3)	1.2005	1.4819	0.7246
IR1(BF4)	1.1264	1.3356	0.6741
IR1(BF5)	1.3388	1.7938	0.7425
IR1(BF6)	1.2607	1.6183	0.7022
IR1(BF7)	1.1736	1.4355	0.654
IR1(BF8)	1.102	1.2962	0.6164

Table 5.9 shows the location and size of FCLs.for min f2. It can be seen that 7 FCL’s for minimizing the total size of FCL is required. The biggest FCL is placed between bus 1 and bus 6 having the resistance and reactance values of 0.0846 pu and 0.7431 pu respectively. Thus, this solution cannot be the ultimate solution.

Table 5.9 FCL locations and size pu (f2)

From bus	**To bus**	**Rpu**	**Xpu**
0	1	0.0000	0.0000
1	2	0.0000	0.6375
2	3	0.0000	0.0000
3	4	0.0007	0.0000
4	5	0.0000	0.0096
1	6	0.0846	0.7431

From bus	**To bus**	**Rpu**	**Xpu**
6	7	0.0000	0.0000
7	8	0.0000	0.0035
8	9	0.0000	0.0000
6	0	0.0000	0.0013
2	0	0.1452	0.0668

The per-unit voltage at various buses at fault conditions are shown in Table 5.10. Here, F1 to F9 represent the buses where the fault has been simulated and B1 to B9 represent the buses where the voltage profile is to be observed. The element with row B1 and column F9 has a value of 0.673 pu means that the per-unit voltage at bus 1 is 0.673 pu when the fault occurs at bus 9.

Table 5.10 Voltage pu during various fault conditions (f2)

Vfault	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
B1	0.0000	0.550	0.579	0.604	0.635	0.593	0.618	0.648	0.673
B2	0.261	0.000	0.083	0.147	0.218	0.699	0.717	0.739	0.757
B3	0.261	0.000	0.000	0.068	0.144	0.699	0.717	0.739	0.757
B4	0.261	0.000	0.000	0.000	0.081	0.699	0.717	0.739	0.757
B5	0.261	0.000	0.000	0.000	0.000	0.699	0.717	0.739	0.757
B6	0.304	0.686	0.708	0.725	0.747	0.000	0.073	0.153	0.216
B7	0.304	0.686	0.708	0.725	0.747	0.000	0.000	0.085	0.152
B8	0.304	0.686	0.708	0.725	0.747	0.000	0.000	0.000	0.071
B9	0.304	0.686	0.708	0.725	0.747	0.000	0.000	0.000	0.000

5.1.2.3 Minimization of the number of FCL (f3) as the main objective function

When minimization of the number of FCL (f3) is taken as the main objective function, the value of the objective functions are shown in Table 5.11. The current minimization index is 6.888 pu, the size of FCL is 2.664 pu, the number of FCL is 1 and the voltage sag minimization index is 0.889 pu.

Table 5.11 Objective function values when f3 is the main objective function

Index	**f1**	**f2**	**f3**	**f4**
73	6.888	2.664	1	0.889

Table 5.12 shows the fault current flowing through various protective devices. It can be seen that when there is no DG, the fault current flowing through fuse 1 (IF1) is 1.3572 pu. After the integration of DG in the system, the fault current increases to 2.3676 pu. Finally, after adding FCL, the fault current is decreased to 1.3494 pu. Thus, the fault current with FCL is maintained close to the value without DG.

Table 5.12 Fault current flowing through the protective device (f3)

Device Fault Current	**Without DG**	**With DG**	**With FCl**
IF1	1.3572	2.3676	1.3494
IF2	1.2692	2.111	1.2671
IF3	1.2005	1.9227	1.2018
IF4	1.1264	1.7328	1.1304
IF5	1.3388	2.3359	1.3457
IF6	1.2607	2.1073	1.2716
IF7	1.1736	1.8693	1.1875
IF8	1.102	1.6879	1.1173
IR1(P)	1.4327	1.9647	0.2975
IR2(P)	1.4327	1.9673	0.2975
IR1(BF1)	1.3572	1.8249	0.8045
IR1(BF2)	1.2692	1.627	0.7554
IR1(BF3)	1.2005	1.4819	0.7165
IR1(BF4)	1.1264	1.3356	0.674
IR1(BF5)	1.3388	1.7938	0.8009

IR1(BF6)	1.2607	1.6183	0.7568
IR1(BF7)	1.1736	1.4355	0.7067
IR1(BF8)	1.102	1.2962	0.665

Table 5.13 shows the position and size of FCL for min f3. It can be seen that only one FCL with an inductive value of 2.664 pu is required between the substation and bus 1.

Table 5.13 FCL locations and size pu (f3)

From bus	**To bus**	**Rpu**	**Xpu**
0	1	0.0000	2.6640

However, the problem with using a single FCL can be seen in other objectives functions. The variation of fault current flowing through fuses, recloser primary and backup protection in the presence and absence of FCL is large. And the voltage sag minimization index (f4) becomes worse which can be reflected in Table 5.14. Here, the element with row B1 and column F9 has a value of 0.268 pu means that the per-unit voltage at bus 1 is 0.268 pu when the fault occurs at bus 9. Thus, this solution cannot be used.

Table 5.14 Voltage pu during various fault conditions (f3)

Vfault	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
B1	0.000	0.043	0.125	0.187	0.251	0.054	0.127	0.206	0.268
B2	0.029	0.000	0.085	0.148	0.215	0.081	0.153	0.230	0.291
B3	0.029	0.000	0.000	0.068	0.140	0.081	0.153	0.230	0.291
B4	0.029	0.000	0.000	0.000	0.076	0.081	0.153	0.230	0.291
B5	0.029	0.000	0.000	0.000	0.000	0.081	0.153	0.230	0.291
B6	0.036	0.077	0.157	0.217	0.280	0.000	0.076	0.158	0.224
B7	0.036	0.077	0.157	0.217	0.280	0.000	0.000	0.087	0.157

B8	0.036	0.077	0.157	0.217	0.280	0.000	0.000	0.000	0.075
B9	0.036	0.077	0.157	0.217	0.280	0.000	0.000	0.000	0.000

5.1.2.4 Minimization of voltage sag (f4) as the main objective function (f4)

When the minimization of voltage sag during the fault condition is taken as the main objective function, the value of the objective functions are shown in Table 5.15. The value of the current minimization index is 10.153 pu, the size of FCL is 2.888 pu, the number of FCL is 11 and the voltage sag minimization index is 0.503 pu.

Table 5.15 Objective function values when f4 is the main objective function

Index	f1	f2	f3	f4
77	10.153	2.888	11	0.505

Table 5.16 shows the fault current through protective devices. It can be seen that when there is no DG, the fault current flowing through fuse 1 (IF1) is 1.3572 pu. After the integration of DG in the system, the fault current increases to 2.3676 pu. Finally, after adding FCL, the fault current is decreased to 1.1318 pu.

Table 5.16 Fault current through protective devices (f4)

Device Fault Current	Without DG	With DG	With FCL
IF1	1.3572	2.3676	1.1318
IF2	1.2692	2.111	1.0533
IF3	1.2005	1.9227	0.9834
IF4	1.1264	1.7328	0.8722
IF5	1.3388	2.3359	1.1935
IF6	1.2607	2.1073	1.1137
IF7	1.1736	1.8693	1.0319
IF8	1.102	1.6879	0.908
IR1(P)	1.4327	1.9647	1.4327
IR2(P)	1.4327	1.9673	1.4327

IR1(BF1)	1.3572	1.8249	0.6946
IR1(BF2)	1.2692	1.627	0.6465
IR1(BF3)	1.2005	1.4819	0.6036
IR1(BF4)	1.1264	1.3356	0.5353
IR1(BF5)	1.3388	1.7938	0.7388
IR1(BF6)	1.2607	1.6183	0.6894
IR1(BF7)	1.1736	1.4355	0.6387
IR1(BF8)	1.102	1.2962	0.5621

Table 5.17 shows the position and size of the FCL. In this case, there are 11 FCLs with the biggest FCL with the resistance and reactance of 1.03764 pu and 0.30051 pu respectively being placed between bus 1 and bus 2. The use of 11 FCL’s for minimizing the voltage sag during fault condition is not feasible and thus, this solution cannot be the ultimate solution.

Table 5.17 FCL locations and size pu (f4)

From bus	**To bus**	**Rpu**	**Xpu**
0	1	0.00071	0.00000
1	2	1.03764	0.30051
2	3	0.00060	0.00141
3	4	0.00087	0.01445
4	5	0.00000	0.07706
1	6	0.77890	0.40879
6	7	0.00949	0.00014
7	8	0.00231	0.00126
8	9	0.05719	0.04646
6	0	0.00000	0.02449
2	0	0.12617	0.00000

Table 5.18 shows the per-unit voltage during various fault conditions. The element with row B1 and column F9 has a value of 0.787 pu means that the per-unit voltage at bus 1 is 0.787 pu when the fault occurs at bus 9. It can be seen that the per-unit voltage of bus 1 has improved significantly when the fault occurs at bus 9 as compared to other cases.

Table 5.18 Voltage pu during various fault conditions (f4)

Vfault	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
B1	0.000	0.784	0.801	0.813	0.824	0.698	0.725	0.750	0.787
B2	0.455	0.000	0.072	0.133	0.229	0.882	0.897	0.909	0.927
B3	0.455	0.000	0.000	0.067	0.172	0.882	0.897	0.909	0.927
B4	0.455	0.000	0.000	0.000	0.115	0.882	0.897	0.909	0.927
B5	0.455	0.000	0.000	0.000	0.000	0.882	0.897	0.909	0.927
B6	0.385	0.919	0.927	0.931	0.931	0.000	0.075	0.148	0.258
B7	0.385	0.919	0.927	0.931	0.931	0.000	0.000	0.078	0.196
B8	0.385	0.919	0.927	0.931	0.931	0.000	0.000	0.000	0.127
B9	0.385	0.919	0.927	0.931	0.931	0.000	0.000	0.000	0.000

5.1.2.5 Main/Compromise solution

When analyzing all the four cases considering each of the objective function as the main objective function one at a time, it can be seen that while trying to reach for the minimum solution for one objective function, all other three objective functions get degraded. Thus, a compromise solution which minimizes each of the objective function to an extent that is acceptable and meets the required target is chosen as the main solution for this thesis. The compromise solution considering all the objective function is shown in Table 5.19. The value of current minimization index is 8.867 pu, the size of FCL is 3.093 pu, the number of FCL is 2 and the voltage sag minimization index is 0.530 pu.

Table 5.19 Objective function values for main solution

Index	f1	f2	f3	f4
4	8.867	3.093	2	0.530

Table 5.20 shows the position and size of the FCL. The final solution consists of 2 FCLs which are placed between buses 1-2 and buses 1-6 respectively. The FCL between bus 1-2 has a reactance of 1.3499 pu and the FCL between bus 1-6 has a resistance of 1.0806 pu and reactance of 0.6623 pu respectively.

Table 5.20 FCL location and sizes (Main Solution)

S.No	From bus	To bus	Rpu	Xpu
1	1	2	0.0000	1.3499
2	1	6	1.0806	0.6623

Table 5.21shows the fault current flowing through various protective devices. It can be seen that when there is no DG, the fault current flowing through fuse 1 (IF1) is 1.3572 pu. After the integration of DG in the system, the fault current increases to 2.3676 pu. Finally, after adding FCL, the fault current is decreased to 1.058 pu.

Table 5.21 Fault current through the protective device (Main Solution)

Device Fault Current	Without DG	With DG	With FCl
IF1	1.3572	2.3676	1.058
IF2	1.2692	2.111	1.0072
IF3	1.2005	1.9227	0.9662
IF4	1.1264	1.7328	0.9206
IF5	1.3388	2.3359	1.0509
IF6	1.2607	2.1073	0.994
IF7	1.1736	1.8693	0.9316
IF8	1.102	1.6879	0.8808
IR1(P)	1.4327	1.9647	1.4327
IR2(P)	1.4327	1.9673	1.4327

IR1(BF1)	1.3572	1.8249	0.5131
IR1(BF2)	1.2692	1.627	0.4885
IR1(BF3)	1.2005	1.4819	0.4686
IR1(BF4)	1.1264	1.3356	0.4464
IR1(BF5)	1.3388	1.7938	0.5803
IR1(BF6)	1.2607	1.6183	0.5488
IR1(BF7)	1.1736	1.4355	0.5144
IR1(BF8)	1.102	1.2962	0.4863

Table 5.22 shows the per-unit voltage during various fault conditions. The element with row B1 and column F9 has a value of 0.823 pu means that the per unit voltage at bus 1 is 0.823 pu when the fault occurs at bus 9.

Table 5.22 Voltage pu during various fault conditions (Main Solution)

Vfault	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**F9**
B1	0.000	0.711	0.724	0.736	0.749	0.773	0.791	0.809	0.823
B2	0.431	0.000	0.067	0.119	0.175	0.864	0.875	0.886	0.894
B3	0.431	0.000	0.000	0.055	0.114	0.864	0.875	0.886	0.894
B4	0.431	0.000	0.000	0.000	0.062	0.864	0.875	0.886	0.894
B5	0.431	0.000	0.000	0.000	0.000	0.864	0.875	0.886	0.894
B6	0.479	0.824	0.836	0.845	0.856	0.000	0.060	0.124	0.176
B7	0.479	0.824	0.836	0.845	0.856	0.000	0.000	0.068	0.123
B8	0.479	0.824	0.836	0.845	0.856	0.000	0.000	0.000	0.059
B9	0.479	0.824	0.836	0.845	0.856	0.000	0.000	0.000	0.000

The compromise solution is chosen for this thesis and it is shown that the compromise solution is good enough to restore the recloser fuse coordination in the system which was disturbed after the addition of the synchronous generator in the distribution system. Figure 5.1 to Figure 5.5 shows the per-unit voltages from bus 1 to bus 9 for the fault for three different cases: with DG, without DG and with FCL. As shown by Figure 5.5, without DG when the fault occurs at bus 9, the per-unit voltage of bus 1 to bus 5 is nearly 0.5 pu. After the integration of DG, the per-unit voltage of these buses increases approximately to 0.45 pu. Further, with the addition of FCL, the per-unit voltage improves and is maintained nearly to 0.9pu. Thus, the optimization solution has minimized the voltage sag problem.

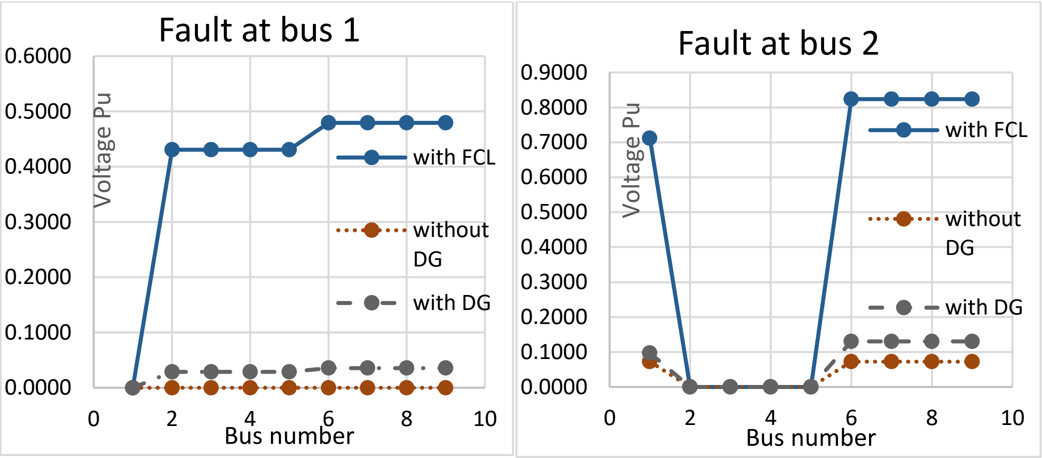

Figure 5.1 Vpu at various buses for fault at bus 1 and bus 2 respectively.

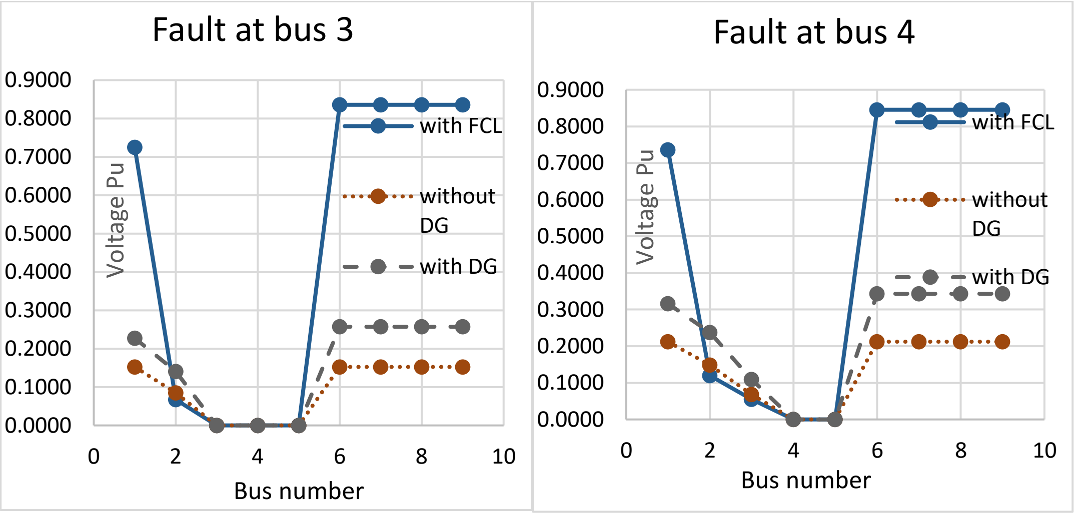

Figure 5.2 Vpu at various buses for fault at bus 3 and bus 4 respectively.

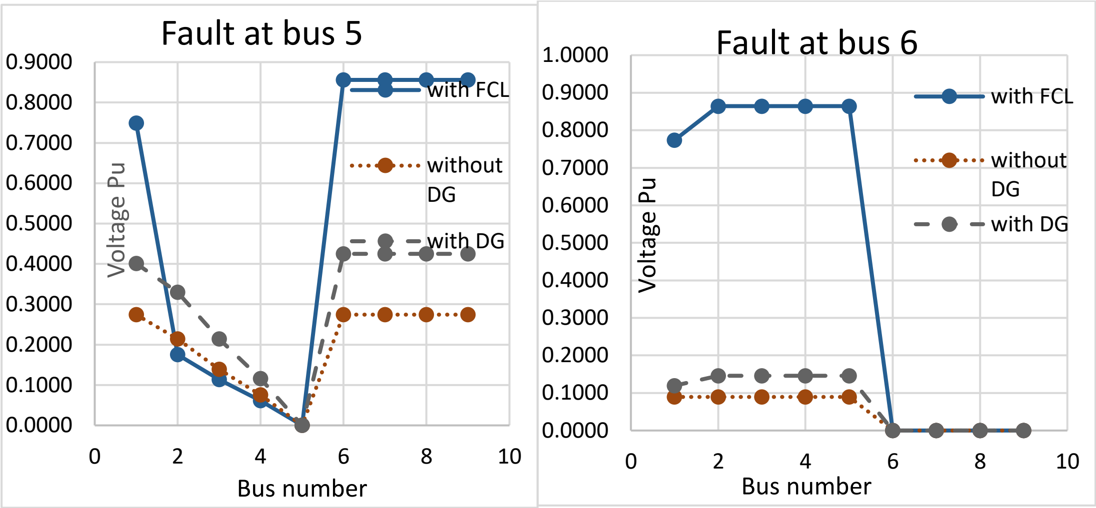

Figure 5.3 Vpu at various buses for fault at bus5 and bus 6 respectively.

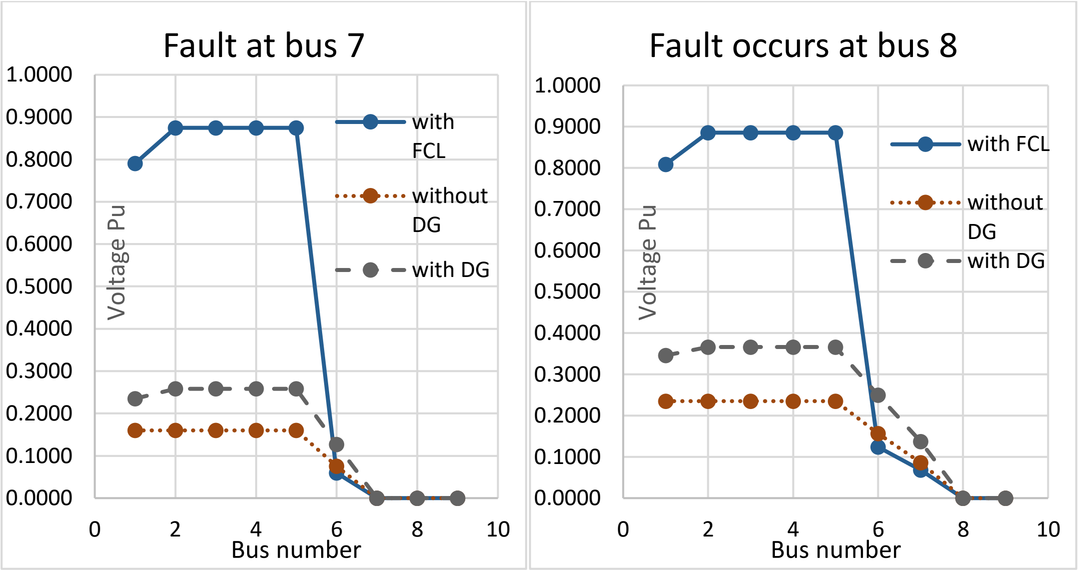

Figure 5.4 Vpu at various buses for fault at bus7 and bus 8 respectively

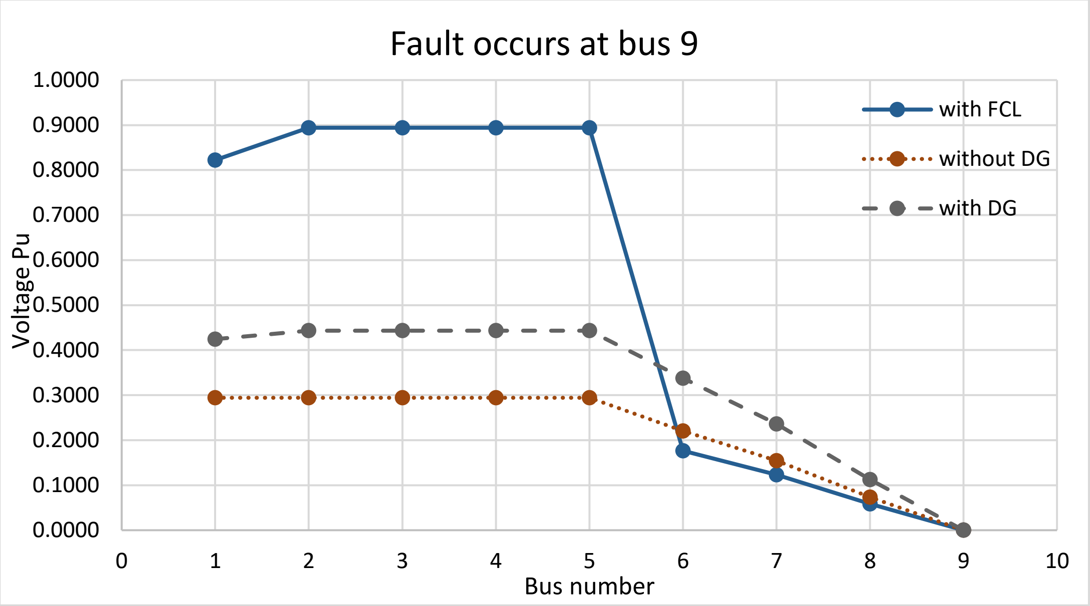

Figure 5.5 Per unit voltage at various buses for fault at bus 9

The solution obtained in this thesis for Canadian Bench Mark Test System is compared with the solution of [2]. The solution of [2] suggested using 11 FCL’s for maintaining protection coordination. This is a large number for a 9 bus system and practically infeasible. But the solution obtained in this thesis suggests that only 2 FCL’s are required but at the cost of degrading the first objective function value. Because of this, the variation of fault current flowing through protective devices with FCL and without DG is large. However, it will be shown that the solution can also maintain protection coordination regardless of the large variation of fault current with FCL and without DG. For this, the solution will be tested and verified in ETAP.

5.1.3 Result Verification in ETAP

In this thesis, ETAP software has been used to check the protection co-ordination between recloser and fuse. The recloser has been simulated by using two directional overcurrent relay elements: the first relay is set to operate very fast as recloser fast mode, while the other relay is set at higher pickup and time dial to operate as the slow mode. Both the relays operate on the same breaker to simulate the recloser

To check the recloser fuse coordination, the fault has been simulated at bus 2 and the sequence of operation of the protective device during the fault has been observed. The Recloser Fuse Coordination is said to be maintained if the recloser fast mode operates before the fuse. Three cases are considered: without DG, with DG and with FCL has been observed.

First, the protection co-ordination is checked for the system without the integration of DG. The time taken by the various protective devices to clear the fault at bus 2 is shown in Table 5.23. It can be seen that the relay of recloser fast mode operates in 46.1 ms and the breaker operating time is 20ms. Thus, the total time taken by the recloser fast mode to clear the fault is 66.1 ms. The time taken by the fuse to clear the fault is 73.3ms. Since recloser fast mode clears the fault before the fuse, the protection coordination between recloser and fuse is maintained for this case.

Table 5.23 Sequence of operation for fault at bus 2 in the absence of DG set and FCL

Time(ms)	**Element**	**If(kA)**	**T1(ms)**	**T2(ms)**	**Condition**
46.1	Recloser fast 1	6.283	< 46.1		Phase-OC-51-Forward
66.1	CB 5		20		Tripped by Recloser fast 1 Phase- OC-51-Forward
73.3	Fuse 1	6.283	44.7	73.3	
638	Recloser slow 1	6.283	638		Phase-OC-51-Forward
758	CB 5		20		Tripped by Recloser slow 1 Phase- OC-51-Forward

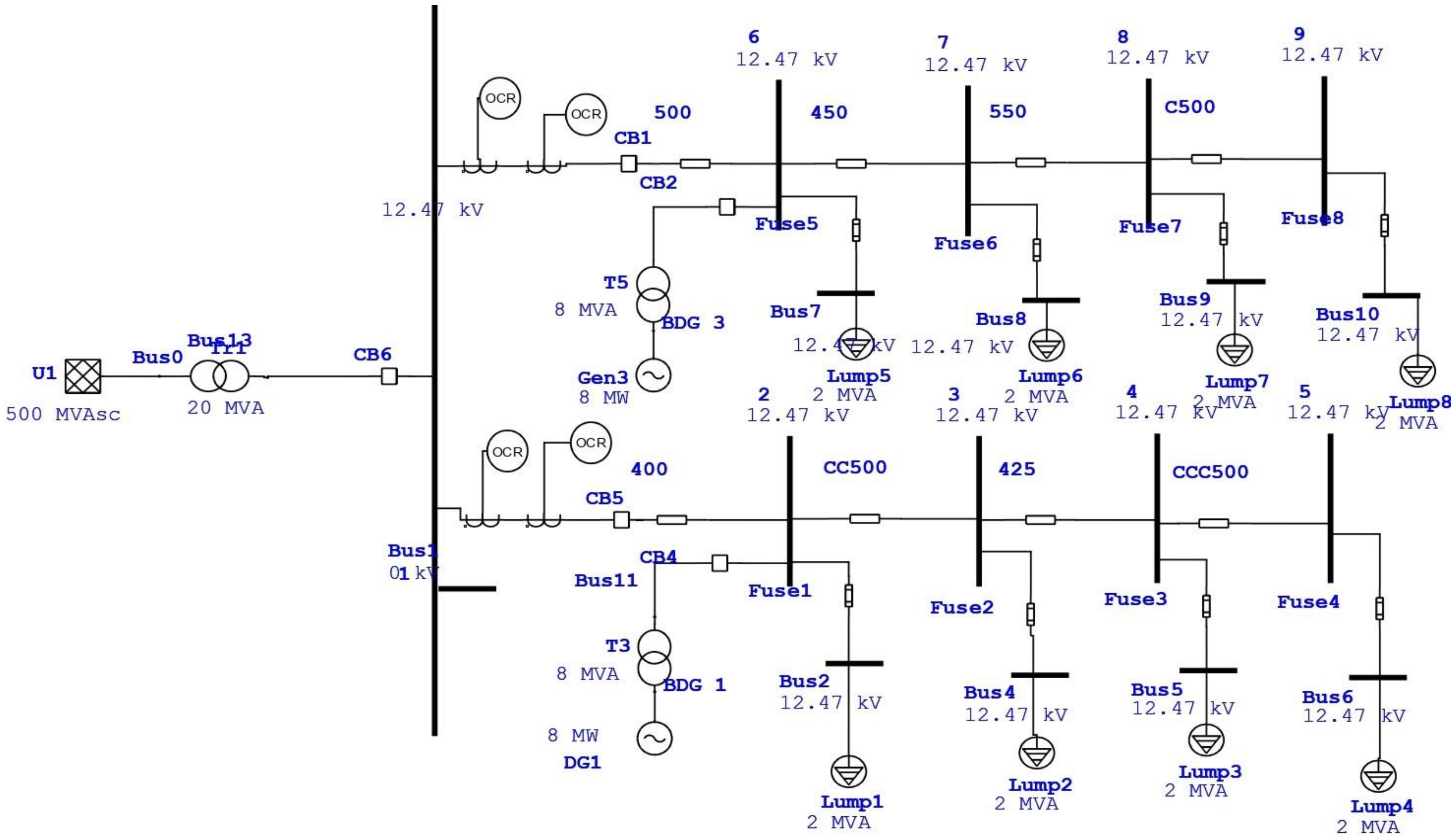

Figure 5.6 Simulation of Canadian Benchmark Test System in ETAP

Second, the protection coordination is checked for the system after the integration of DG. The time taken by the various protective devices to clear the fault at bus 2 is shown in Table 5.24. It can be seen that the relay of recloser fast mode operates in 46.1 ms and the breaker operating time is 20ms. Thus, the total time taken by the recloser fast mode to clear the fault is 66.1 ms. The time taken by the fuse to clear the fault is only 37 ms. Since the fuse clears the fault before the recloser fast mode, the protection coordination between recloser and fuse is not maintained for this case.

Table 5.24 Sequence of operation for fault at bus 2 in the presence of DG set but no FCL

Time(ms)	**Element**	**If(kA)**	**T1(ms)**	**T2(ms)**	**Condition**
37	Fuse 1	10.962	< 20	< 37	
46.1	Recloser fast 1	8.449	< 46.1		Phase-OC-51-Forward
66.1	CB 5		20		Tripped by Recloser fast 1 Phase- OC-51-Forward
581	Recloser slow 1	8.449	581		Phase-OC-51-Forward
601	CB 5		20		Tripped by Recloser slow 1 Phase- OC-51-Forward

Finally, the protection coordination is checked for the system after installing FCL in DG integrated distribution system. The time taken by the various protective devices to clear the fault at bus 2 is shown in Table 5.25. It can be seen that the relay of recloser fast mode operates in 62.5 ms and the breaker operating time is 20ms. Thus, the total time taken by the recloser fast mode to clear the fault is 82.5 ms. The time taken by the fuse to clear the fault is 111 ms. Since recloser fast mode clears the fault before the fuse, the protection coordination between recloser and fuse is again maintained for this case. Thus, it is seen that the protection coordination is disturbed after the integration of DG system and again restored after adding FCL.

Table 5.25 Sequence of operation for fault at bus 2 in the presence of FCL

Time(ms)	**Element**	**If(kA)**	**T1(ms)**	**T2(ms)**	**Condition**
62.5	Recloser fast 1	2.376	62.5		Phase-OC-51-Forward
82.5	CB 5		20		Tripped by Recloser fast 1 Phase- OC-51-Forward
111	Fuse 1	4.889	69.3	111	
1406	Recloser slow 1	2.376	1406		Phase-OC-51-Forward
1426	CB 5		20		Tripped by Recloser slow 1 Phase- OC-51-Forward

5.2 IEEE 69 Bus Test System

5.2.1 Multiple Objective Optimization Problem

The optimization result for this test system is shown APPENDIX D. The table shows that there are many non-dominated solutions. The best solution that is chosen in this thesis is the fifth one. This is the solution that restores protection coordination, requires less number and small size of FCL and satisfactory voltage sag. This solution is shown in Table 5.26 The current minimization index is 28.276 pu, the size of FCL is 1.978 pu, the number of FCL is 12 and the voltage sag minimization index is 0.492 pu.

Table 5.26 Main solution for IEEE 69 bus system

Index	f1	f2	f3	f4
5	28.276	1.978	12	0.492

Figure 5.7 and Figure 5.8 shows the fault current flowing through fuses and reclosers for IEEE 69 bus system for three different cases: without DG, with DG and with FCL. It can be seen that the fault current flowing through fuses and reclosers after synchronizing DG to the distribution system is greater than the fault current flowing through fuse and recloser before synchronization. After inserting the FCL at the location with the size shown in Table 5.28, the fault current flowing through the fuse and reclosers with FCL is maintained close to the value without DG. It can be observed that the curve with FCL nearly fits the curve without DG. Thus, this reduction of fault current by the addition of FCL will help to maintain protection coordination between recloser and fuse.

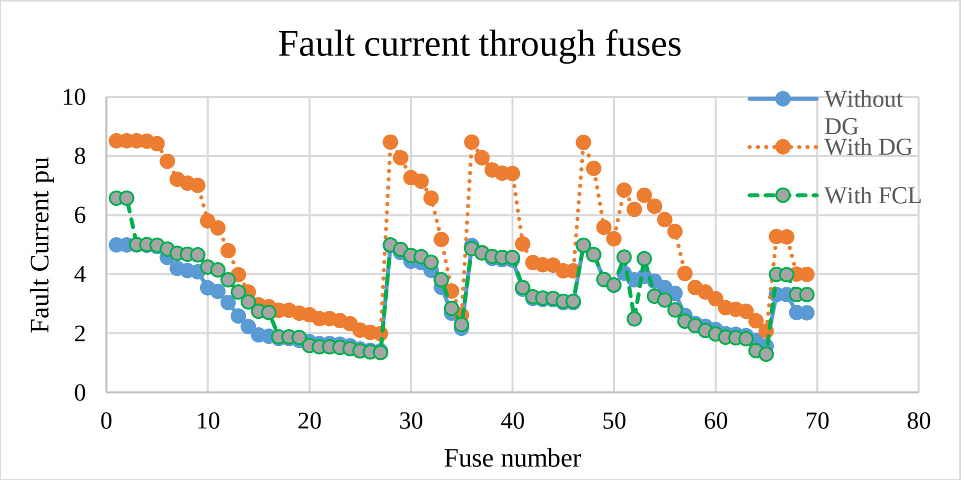

Figure 5.7 Fault current flowing through fuses for IEEE 69 bus system

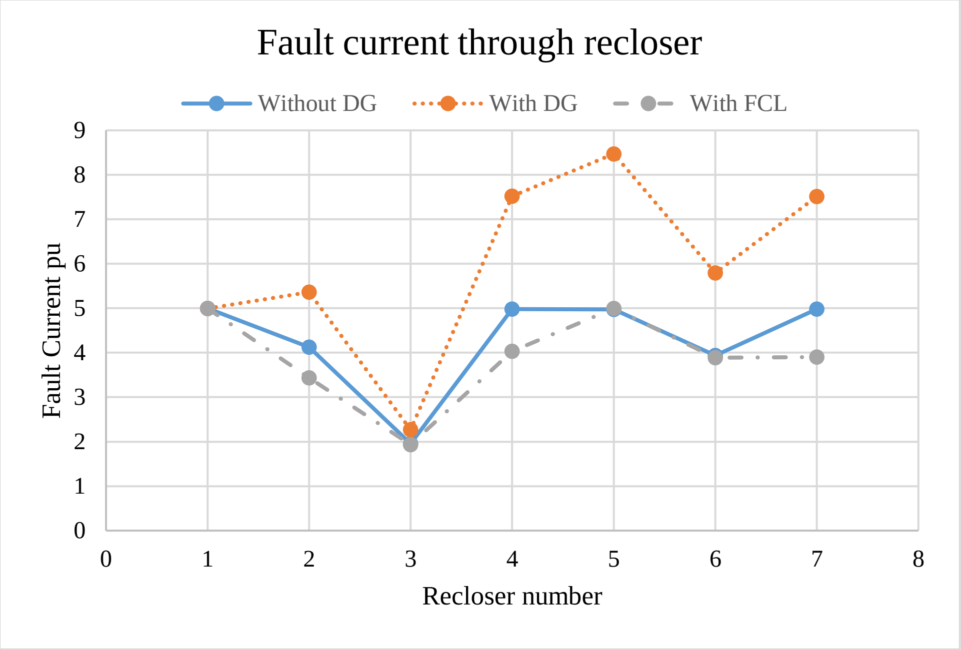

Figure 5.8 Fault current flowing through reclosers for IEEE 69 bus system

Other than maintaining recloser fuse coordination, it is also observed that the voltage sag problem and loss of healthy section load due to low bus voltage at fault condition is reduced significantly as the per-unit voltage is improved significantly after the addition of the FCL. Table 5.27 shows voltage sag minimization inde for three different cases. When there is no DG, the voltage sag indes in the IEEE 69 bus system is 0.675 pu. After the synchronization of the DG sets, the voltage sag decreases to 0.5311 pu. With the addition of FCL whose sizes were calculated by using MOPSO algorithm, the voltage sag minimization index further decreases to 0.4919 pu.

Table 5.27 Voltage sag minimization index for IEEE 69 bus system

Cases	**f4**
Without DG	0.6750
With DG	0.5311
With FCL	0.4919

Figure 5.9 shows the per-unit voltage at bus 23 when the fault occurs at various buses for three different cases: without DG, with DG and with FCL. The x-axis represents the bus where the fault is simulated. It is observed that without DG, the per-unit voltage of bus 23 at-fault condition is zero for the fault occurring till and at bus 23. When there is DG, the voltage of bus 23 for fault at various buses is not zero except for the fault occurring at the bus itself. And with the addition of FCL, the voltage profile is further improved during the fault condition as the voltage sag minimization index is the lowest which can be seen in Figure 5.9.

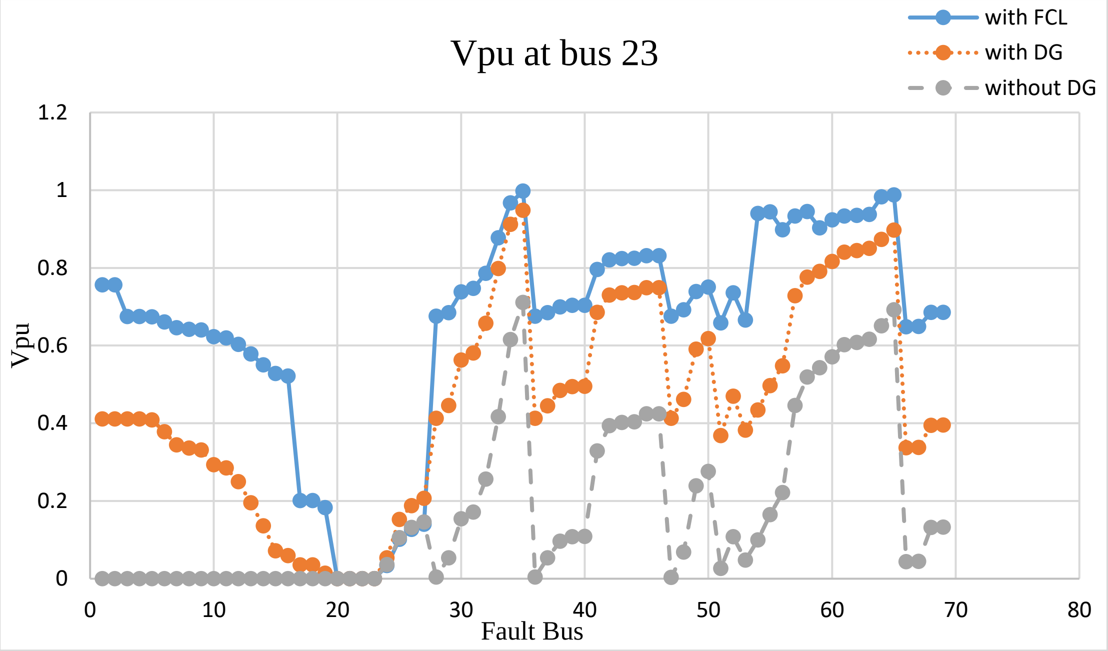

Figure 5.9 Vpu at various buses during fault conditions for IEEE 69 bus system

Table 5.28 shows the position and size of FCL for IEEE 69 bus system. It can be seen that 12 FCLs are required which are placed between buses: 0-59, 2-3, 14-15, 16-17, 19-20, 3-36, 51-52, 53-54, 55-56, 58-59, 59-60 and 63-64

Table 5.28 FCL Location and Size for IEEE 69 bus system

S. No.	From Bus	To Bus	Rpu	Xpu
1	0	59	0.120	0.000
2	2	3	0.000	0.307
3	14	15	0.000	0.027

4	16	17	0.392	0.000
5	19	20	0.174	0.000
6	3	36	0.000	0.009
7	51	52	0.000	0.178
8	53	54	0.175	0.000
9	55	56	0.000	0.079
10	58	59	0.000	0.310
11	59	60	0.030	0.000
12	63	64	0.178	0.000

5.2.2 Result Verification in ETAP

In IEEE 69 bus system, the fault has been simulated at bus 27 and sequence of operation of protective devices are observed for three cases: without DG, with DG and with FCL. First, the protection co-ordination is checked for the system without the integration of DG. The time taken by the various protective devices to clear the fault at bus 27 is shown in Table 5.29. It can be seen that the relay of recloser fast mode operates in 19.4 ms and the breaker operating time is 20ms. Thus, the total time taken by the recloser fast mode to clear the fault is 39.4 ms. The time taken by the fuse to clear the fault is 47.8 ms. Since recloser fast mode clears the fault before the fuse, the protection coordination between recloser and fuse is maintained for this case.

Table 5.29 Sequence of operation for fault at bus 2 in the absence of DG set and FCL

Time (ms)	**ID**	**If (kA)**	**T1 (ms)**	**T2 (ms)**	**Condition**
19.4	Recloser fast4	2.26		<19.4	Phase - OC1 - 51 - Forward
39.4	CB10		20.0		Tripped by Recloser fast4 Phase - OC1 - 51 – Forward
47.8	Fuse27	2.26		47.8	
			23.8		
581	Recloser slow4	2.26		<581	Phase - OC1 - 51 – Forward
601	CB10		20.0		Tripped by Recloser slow4 Phase - OC1 - 51 – Forward
23832	Recloser slow	2.26		23832	Phase - OC1 - 51 – Forward
23852	CB5		20.0		Tripped by Recloser slow Phase - OC1 - 51 - Forward

Second, the protection coordination is checked for the system after the integration of DG. The time taken by the various protective devices to clear the fault at bus 27 is shown in Table 5.30. It can be seen that the relay of recloser fast mode operates in 19.4

ms and the breaker operating time is 20ms. Thus, the total time taken by the recloser fast mode to clear the fault is 39.4 ms. The time taken by the fuse to clear the fault is only 23 ms. Since fuse clears the fault before the recloser fast mode, the protection coordination between recloser and fuse is not maintained for this case.

Table 5.30 Sequence of operation for fault at bus 2 in the presence of DG set but no FCL

Time (ms)	**ID**	**If (kA)**	**T1 (ms)**	**T2 (ms)**	**Condition**
19.4	Recloser fast4	3.43		<19.4	Phase - OC1 - 51 - Forward
23	Fuse27	3.87	<10.0	23.0	
39.4	CB10		20.0		Tripped by Recloser fast4 Phase - OC1 - 51 - Forward
581	Recloser slow4	3.43		<581	Phase - OC1 - 51 - Forward
601	CB10		20.0		Tripped by Recloser slow4 Phase - OC1 - 51 - Forward
23933	Recloser slow	2.26		23933	Phase - OC1 - 51 - Forward
23953	CB5		20.0		Tripped by Recloser slow Phase - OC1 - 51 - Forward

Finally, the protection coordination is checked for the system after installing FCL in DG integrated distribution system. The time taken by the various protective devices to clear the fault at bus 2 is shown in Table 5.31. It can be seen that the relay of recloser fast mode operates in 19.4 ms and the breaker operating time is 20 ms. Thus, the total time taken by the recloser fast mode to clear the fault is 39.4 ms. The time taken by the fuse to clear the fault is 45.1 ms. Since recloser fast mode clears the fault before the fuse, the protection coordination between recloser and fuse is again maintained for this case. Thus, it is seen that the protection coordination is disturbed after the integration of DG system and again restored after adding FCL.

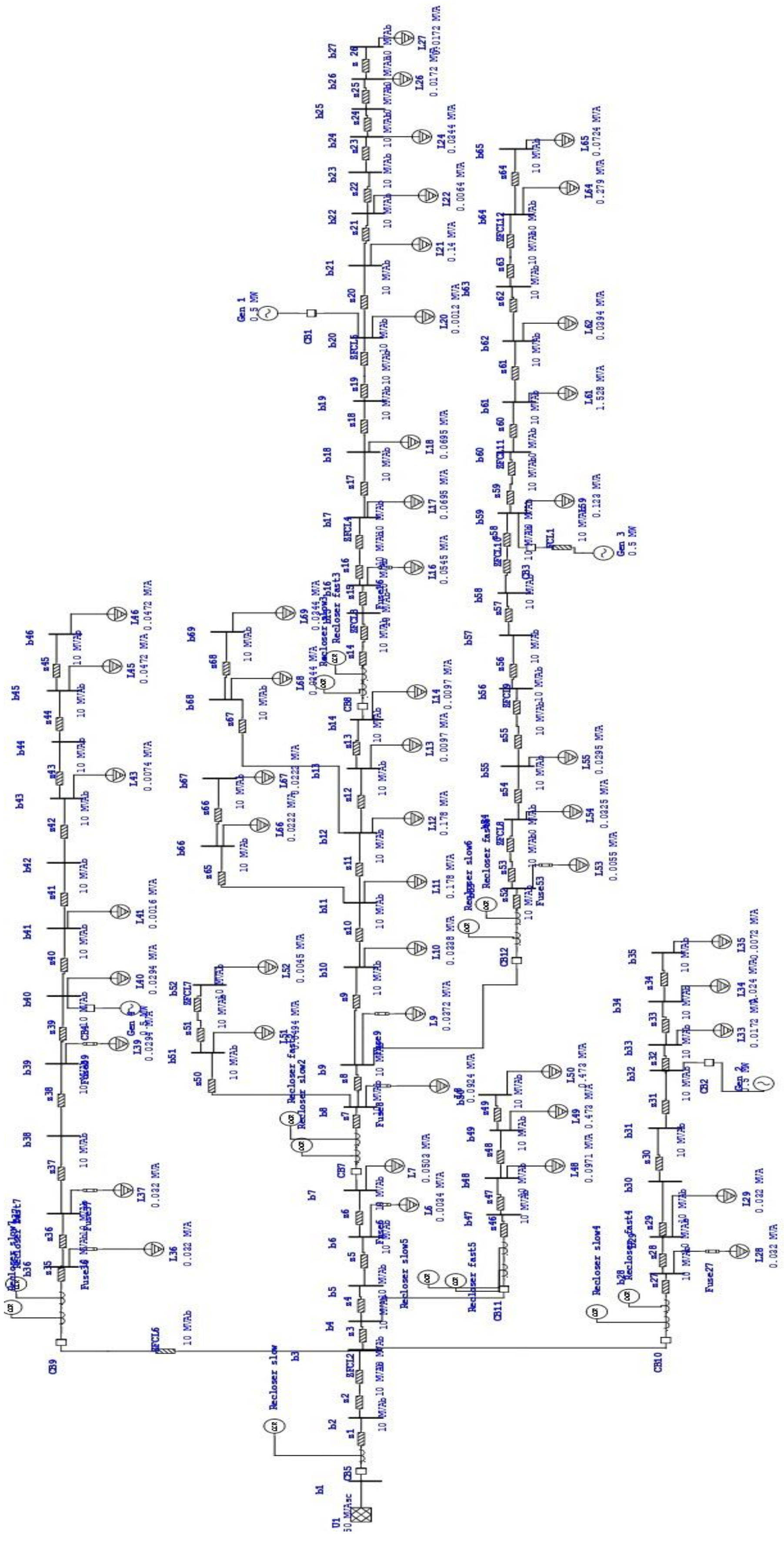

Figure 5.10 Simulation of IEEE 69 test bus System in ETAP

Table 5.31 Sequence of operation for fault at bus 2 in the presence of FCL

Time (ms)	**ID**	**If (kA)**	**T1 (ms)**	**T2 (ms)**	**Condition**
19.4	Recloser fast4	1.91		<19.4	Phase - OC1 - 51 - Forward
39.4	CB10		20.0		Tripped by Recloser fast4 Phase - OC1 - 51 - Forward
45.1	Fuse27	2.35	21.9	45.1	
581	Recloser slow4	1.91		<581	Phase - OC1 - 51 - Forward
601	CB10		20.0		Tripped by Recloser slow4 Phase - OC1 - 51 - Forward

CHAPTER 6. CONCLUSION

There is a high chance that the protection coordination between protective devices will be disturbed due to the inclusion of synchronous DG sets in the distribution system as these DG units also contribute to the fault current in addition to the substation. With the integration of DG, the lateral fuses may operate before the recloser fast mode even for temporary fault. This means that protection coordination fails for a temporary fault as the fault current exceeds the maximum limit of the coordination zone. Thus, the fault current should be reduced. In such a situation, FCLs can be used to limit the fault current and restore protection coordination. However, the cost of FCL should also be considered. The number and size of FCL should be minimum to minimize the cost, but should also maintain protection coordination and minimize the voltage sag problem. This requires optimal planning of FCL which can be done using MOPSO algorithm.

Here, in this thesis, the optimal planning of FCL was done for two test system. For Canadian Bench Mark Test System, only two FCL with a total size of 3.093 pu was obtained. The FCL should be located between bus 1-2 and bus 1-6 respectively. The current minimization and voltage minimization indices obtained were 8.867 pu and 0.530 pu respectively. For IEEE 69 bus test system, only 12 FCLs with a total size of 1.978 pu was required. The current minimization and voltage minimization indices obtained were 28.276 pu and 0.492 pu respectively. This thesis suggests fewer number of FCL which can restore protection coordination and minimize voltage sag problem simultaneously. To guarantee the protection coordination between recloser and fuse, the system is simulated in ETAP and the sequence of operation of protective devices for fault at various is observed. The simulation in ETAP shows that the before connection of DG in the distribution system, the protection coordination between recloser and fuse is well maintained. But after integration of DG, the fuses operate before the recloser fast mode and the protection coordination is disturbed. When FCL's whose size and location calculated from MOPSO algorithm is used, the recloser fuse coordination is restored which can be seen from the fact that the recloser fast mode operates before the fuse. Thus, optimal planning of FCL can restore recloser fuse coordination.

PUBLICATION

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APPENDICES

APPENDIX A Line and Nominal Load Data for IEEE 69 bus system

Branch no	Sending end	Receiving end	R(Ω)	X(Ω)	P (kW)	Q (kVAR)
1	1	2	0.0005	0.001	0	0
2	2	3	0.0005	0.001	0	0
3	3	4	0.002	0.004	0	0
4	4	5	0.025	0.029	0	0
5	5	6	0.366	0.186	2.6	2.2
6	6	7	0.381	0.194	40.4	30
7	7	8	0.092	0.047	75	54
8	8	9	0.049	0.025	30	22
9	9	10	0.819	0.271	28	19
10	10	11	0.187	0.062	145	104
11	11	12	0.711	0.235	145	104
12	12	13	1.03	0.34	8	5
13	13	14	1.044	0.34	8	5
14	14	15	1.058	0.35	0	0
15	15	16	0.197	0.065	45	30
16	16	17	0.374	0.124	60	35
17	17	18	0.005	0.002	60	35
18	18	19	0.328	0.108	0	0
19	19	20	0.211	0.069	1	0.6
20	20	21	0.342	0.113	114	81
21	21	22	0.014	0.005	5	3.5
22	22	23	0.159	0.053	0	0
23	23	24	0.346	0.115	28	20
24	24	25	0.749	0.248	0	0
25	25	26	0.309	0.102	14	10
26	26	27	0.173	0.057	14	10

27	3	28	0.004	0.011	26	18.6
28	28	29	0.064	0.157	26	18.6
29	29	30	0.398	0.132	0	0
30	30	31	0.07	0.023	0	0
31	31	32	0.351	0.116	0	0
32	32	33	0.839	0.282	14	10
33	33	34	1.708	0.565	19.5	14
34	34	35	1.474	0.487	6	4
35	3	36	0.004	0.011	26	18.55
36	36	37	0.064	0.157	26	18.55
37	37	38	0.105	0.123	0	0
38	38	39	0.03	0.036	24	17
39	39	40	0.002	0.002	24	17
40	40	41	0.728	0.851	1.2	1
41	41	42	0.31	0.362	0	0
42	42	43	0.041	0.048	6	4.3
43	43	44	0.009	0.012	0	0
44	44	45	0.109	0.137	39.22	26.3
45	45	46	0.0009	0.001	39.22	26.3
46	4	47	0.003	0.008	0	0
47	47	48	0.085	0.208	79	56.4
48	48	49	0.29	0.709	384.7	274.5
49	49	50	0.082	0.201	384.7	274.5
50	8	51	0.093	0.047	40.5	28.3
51	51	52	0.332	0.114	3.6	2.7
52	9	53	0.174	0.089	4.35	3.5
53	53	54	0.203	0.103	26.4	19
54	54	55	0.284	0.145	24	17.2
55	55	56	0.281	0.143	0	0
56	56	57	1.59	0.534	0	0
57	57	58	0.784	0.263	0	0

58	58	59	0.304	0.101	100	72
59	59	60	0.386	0.117	0	0
60	60	61	0.508	0.259	1244	888
61	61	62	0.097	0.05	32	23
62	62	63	0.145	0.074	0	0
63	63	64	0.711	0.362	227	162
64	64	65	1.041	0.53	59	42
65	11	66	0.201	0.061	18	13
66	66	67	0.005	0.001	18	13
67	12	68	0.739	0.244	28	20
68	68	69	0.005	0.002	28	20

APPENDIX B System Parameter for Canadian Bench Mark Test System

Feeder Data	700 MCM Cu XLPE Cable with $z=0.1529+ j0.1406\ \Omega/\mathrm{km}$
Utility Data	MVAsc= 500MVA and X/R=6
Base MVA	100
Base kV	12.47
DG Reactance(x%)	9.67%
DG Transformer(x%)	5%, 12.47kV/480V

APPENDIX C Pareto Optimal Solutions for Canadian Bench Mark Test System

Index	f1	f2	f3	f4
1	8.683	2.978	9	0.526
2	6.904	2.383	10	0.559
3	6.646	2.590	11	0.561
4	8.867	3.093	2	0.530
5	5.961	2.329	3	0.580
6	8.874	3.042	7	0.529
7	7.811	3.195	8	0.538
8	8.276	3.403	8	0.531
9	8.458	2.564	6	0.536
10	5.847	2.471	5	0.578
11	10.051	2.479	11	0.511
12	10.388	2.728	8	0.516
13	8.298	3.860	9	0.530
14	9.274	3.571	11	0.511
15	9.099	3.082	11	0.518
16	8.260	3.539	11	0.529
17	8.738	3.469	10	0.521
18	9.009	3.170	9	0.521
19	6.487	2.058	5	0.572
20	9.164	3.261	11	0.517
21	10.467	2.059	8	0.509
22	6.052	2.095	11	0.576
23	8.517	3.343	10	0.525
24	5.671	2.022	9	0.582
25	9.234	2.325	9	0.529
26	8.586	3.593	9	0.530
27	6.133	2.579	2	0.888
28	9.974	3.378	10	0.507
29	6.678	2.506	9	0.562
30	5.806	2.228	10	0.577
31	7.549	2.913	7	0.551
32	6.924	2.345	8	0.563
33	11.098	1.930	11	0.514
34	8.223	3.610	9	0.533
35	8.780	3.232	11	0.525
36	10.105	2.285	10	0.512
37	8.851	3.418	10	0.523
38	8.139	1.915	10	0.567
39	9.359	3.040	11	0.517
40	9.612	3.503	10	0.512
41	8.411	2.938	7	0.540
42	10.311	2.481	10	0.511
43	9.903	2.319	10	0.518
44	9.307	3.534	9	0.513
45	10.630	2.955	7	0.517
46	7.935	2.733	10	0.545
47	7.961	3.439	10	0.536
48	6.962	2.803	9	0.555
49	7.710	3.180	9	0.542
50	11.617	1.998	10	0.509
51	8.045	3.232	9	0.536
52	7.470	3.057	10	0.547
53	8.628	3.203	9	0.533
54	5.322	2.178	11	0.588

Index	f1	f2	f3	f4
55	6.121	1.980	11	0.578
56	5.647	2.202	11	0.582
57	5.757	2.157	9	0.579
58	8.705	3.637	11	0.521
59	7.858	2.724	10	0.547
60	7.531	2.873	9	0.548
61	7.386	2.845	11	0.547
62	5.567	1.880	10	0.587
63	7.397	2.718	9	0.552
64	6.993	2.456	10	0.559
65	6.851	2.403	9	0.561
66	7.284	2.527	11	0.552
67	5.919	2.363	9	0.576
68	6.813	2.470	10	0.560
69	8.554	2.307	11	0.542
70	9.048	3.013	10	0.523
71	5.410	2.261	11	0.586
72	8.537	3.854	9	0.529
73	6.888	2.664	1	0.889
74	7.308	2.709	10	0.553
75	7.819	3.122	9	0.542
76	7.573	2.794	8	0.546
77	10.153	2.888	11	0.505
78	9.842	3.244	10	0.508
79	6.032	2.556	11	0.574
80	6.667	2.522	8	0.566
81	5.614	2.413	11	0.580

Index	f1	f2	f3	f4
82	5.731	2.300	9	0.577
83	7.509	2.986	11	0.547
84	8.336	3.720	11	0.528
85	7.036	3.000	11	0.554
86	6.160	2.483	10	0.569
87	7.092	2.673	7	0.557
88	6.724	2.833	9	0.558
89	5.950	2.465	11	0.574
90	6.552	2.697	10	0.562
91	6.698	2.943	11	0.561
92	6.263	2.553	11	0.569
93	9.726	2.379	8	0.527
94	10.383	2.743	8	0.505
95	10.280	2.756	10	0.507
96	9.952	2.202	9	0.523
97	5.178	1.972	9	0.598
98	6.463	2.494	10	0.567
99	7.244	2.927	10	0.551
100	8.653	3.151	11	0.533
101	5.068	4.884	4	0.636
102	8.896	2.567	11	0.536
103	10.038	2.925	9	0.510
104	5.301	2.205	10	0.590
105	7.332	3.077	10	0.549
106	7.983	2.895	8	0.543
107	9.289	2.970	2	0.675
108	8.995	2.543	10	0.526

Index	f1	f2	f3	f4
109	8.071	2.794	10	0.542
110	9.994	2.442	6	0.519
111	9.267	3.347	9	0.519
112	7.212	2.014	11	0.572
113	8.793	2.272	10	0.541
114	9.144	2.822	9	0.521
115	10.662	2.038	10	0.513
116	7.152	3.302	2	0.830
117	8.084	3.131	8	0.541
118	7.025	2.596	7	0.558
119	8.162	2.613	9	0.552
120	6.210	2.411	11	0.574
121	8.384	2.318	11	0.547
122	8.484	2.949	8	0.533
123	6.286	2.346	10	0.574
124	9.741	3.332	10	0.513
125	9.222	2.285	9	0.532
126	7.894	2.012	8	0.566
127	6.017	2.238	10	0.575
128	7.648	2.957	9	0.544
129	10.568	2.046	2	0.760
130	5.579	2.125	11	0.583
131	7.864	3.236	7	0.542
132	6.337	2.575	8	0.570
133	7.728	3.190	9	0.539
134	6.838	2.363	10	0.566
135	5.510	1.969	9	0.596
136	7.129	2.651	9	0.556
137	7.064	2.916	9	0.554
138	8.373	3.436	10	0.530
139	7.775	3.140	11	0.541
140	6.784	2.293	9	0.569
141	8.741	3.121	8	0.531
142	7.907	3.374	9	0.538
143	8.833	2.242	9	0.544
144	7.437	2.989	8	0.556
145	5.436	2.184	9	0.592
146	9.066	2.476	8	0.533
147	7.190	2.759	10	0.554
148	6.234	2.439	10	0.571
149	9.830	2.907	11	0.517
150	7.991	3.257	10	0.535
151	8.457	1.838	9	0.547
152	9.507	2.112	9	0.546
153	9.636	2.061	9	0.543
154	5.254	1.836	10	0.595
155	8.243	3.290	2	0.800
156	9.107	3.545	8	0.529
157	8.227	1.899	8	0.585
158	5.362	2.224	10	0.590
159	6.432	2.319	7	0.578
160	6.645	2.797	8	0.563
161	5.630	2.268	9	0.587
162	9.493	3.271	10	0.515

Index	f1	f2	f3	f4
163	6.503	2.279	8	0.571
164	5.857	2.143	7	0.592
165	8.022	3.317	6	0.549
166	4.575	1.692	7	0.610
167	10.148	1.887	7	0.529
168	8.405	2.431	8	0.552
169	7.659	2.410	6	0.568
170	9.128	3.354	7	0.521
171	7.749	2.627	9	0.556
172	4.983	1.940	8	0.600
173	6.955	2.615	8	0.561
174	9.575	2.242	11	0.542
175	6.362	2.687	9	0.565
176	6.402	2.667	9	0.565
177	8.192	3.230	11	0.538
178	6.063	2.073	8	0.585
179	6.753	2.817	9	0.557
180	4.298	2.391	11	0.640
181	4.033	6.278	10	0.699
182	4.228	6.516	11	0.664
183	4.228	6.516	11	0.664
184	9.597	3.029	11	0.521
185	9.834	3.215	10	0.517
186	6.604	2.449	10	0.567
187	8.940	1.928	8	0.564
188	6.580	2.752	8	0.569
189	6.555	2.055	9	0.571
190	5.520	1.802	8	0.596
191	5.495	2.026	10	0.586
192	7.096	2.342	8	0.564
193	6.820	2.352	11	0.561
194	5.992	1.994	10	0.583
195	4.297	2.017	7	0.642
196	6.103	2.167	8	0.581
197	9.001	2.337	10	0.537
198	7.270	2.842	9	0.554
199	6.383	2.339	7	0.572
200	8.149	2.681	2	0.813

APPENDIX D Pareto Optimal Solutions for IEEE 69 bus System

Index	f1	f2	f3	f4
1	50.865	0.720	12	0.497
2	29.427	1.083	60	0.483
3	41.207	1.028	59	0.471
4	34.825	1.349	7	0.539
5	28.276	1.978	12	0.492
6	41.301	1.164	10	0.478
7	24.320	1.762	67	0.461
8	28.913	1.428	63	0.477
9	40.739	1.145	57	0.478
10	27.811	1.464	62	0.487
11	98.139	0.311	7	0.524
12	37.881	1.227	12	0.512
13	46.153	0.974	15	0.457
14	24.096	2.138	63	0.469
15	44.502	0.950	20	0.495
16	28.475	1.609	58	0.479
17	25.476	1.529	64	0.459
18	22.852	1.959	64	0.453
19	30.214	1.414	56	0.505
20	30.774	1.268	53	0.521
21	29.614	1.433	56	0.496
22	34.607	1.298	45	0.499
23	47.413	1.060	11	0.545
24	24.478	1.747	63	0.455
25	24.676	1.641	70	0.462
26	23.853	1.889	66	0.456
27	31.397	1.528	52	0.471
28	31.529	1.577	12	0.495
29	25.393	1.815	56	0.472
30	41.413	1.128	11	0.474
31	37.256	1.276	13	0.524
32	70.624	0.726	6	0.464
33	33.729	1.618	10	0.482
34	31.756	1.562	42	0.485
35	27.818	1.166	67	0.482
36	26.313	1.496	60	0.476
37	43.595	0.965	57	0.476
38	34.715	1.162	57	0.496
39	34.632	0.933	60	0.485
40	48.873	0.895	56	0.485
41	29.589	1.215	58	0.498
42	75.122	0.726	7	0.519
43	26.698	1.663	51	0.478
44	24.729	1.564	59	0.499
45	41.849	1.051	58	0.499
46	33.603	1.006	66	0.491
47	45.486	0.945	46	0.510
48	48.229	0.925	57	0.503
49	45.058	0.852	61	0.480
50	49.728	0.760	62	0.501
51	23.330	1.787	71	0.454
52	27.899	1.833	21	0.484
53	27.480	1.490	68	0.463
54	56.276	1.025	10	0.490

Index	f1	f2	f3	f4
55	58.136	0.823	6	0.455
56	23.677	2.353	62	0.474
57	23.529	2.546	61	0.470
58	25.952	1.413	70	0.493
59	24.210	1.708	71	0.480
60	24.127	1.728	70	0.470
61	24.146	1.796	66	0.471
62	36.764	1.296	11	0.553
63	22.520	2.263	69	0.447
64	21.939	2.368	71	0.459
65	22.666	1.924	70	0.465
66	28.532	1.674	49	0.482
67	31.072	1.827	19	0.474
68	110.096	25.177	62	0.193
69	111.880	28.982	42	0.176
70	112.860	28.103	69	0.185
71	113.141	32.345	44	0.174
72	113.251	28.848	47	0.172
73	113.532	27.383	66	0.183
74	114.140	28.268	65	0.172
75	114.178	26.220	68	0.183
76	114.328	27.006	66	0.181
77	114.376	27.501	71	0.181
78	114.596	34.242	46	0.169
79	114.623	35.675	49	0.168
80	114.683	36.706	67	0.167
81	114.783	29.442	42	0.171

Index	f1	f2	f3	f4
82	119.423	28.606	71	0.182
83	119.520	22.305	69	0.198
84	119.527	28.514	69	0.182
85	119.546	21.628	41	0.189
86	119.570	30.686	61	0.178
87	119.654	20.862	62	0.200
88	119.698	28.475	42	0.181
89	119.711	41.328	69	0.175
90	119.734	40.471	71	0.172
91	119.763	32.802	43	0.175
92	119.778	20.031	70	0.203
93	119.792	39.327	72	0.174
94	119.848	44.155	67	0.172
95	119.871	21.239	40	0.207
96	119.926	31.510	45	0.178
97	119.930	24.359	40	0.184
98	119.973	21.068	42	0.209
99	119.980	32.355	69	0.176
100	120.066	38.040	69	0.174