Protection Coordination in Microgrid Using Fault Current Limiters

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Abstract

To ensure the seamless working of the microgrid, another Smart Grid tool- the Fault current limiter (FCL) has been proposed to suppress the fault currents to the level such that the requisite protection coordination is possible. The FCL suppresses the fault currents from the utility grid and acts as a solution to the directional overcurrent relay coordination problem within the microgrid. The FCLs are unique in the way that they are 'invisible' during the normal unfaulted operation of the power system but come into picture at the time of fault. The contributing reactance from the FCL is instrumental in reducing the fault currents flowing inside the microgrid from the incoming transmission feeder during the time of fault. In this paper reactance FCLs are only being used for coordination of directional overcurrent relay (DOCR) settings. Symmetrical three phase faults are considered for relay coordination. The distributed generation (DG) considered here is the conventional synchronous generator directly connected to the medium voltage networks. The proposed solution is

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tested on a radial distribution system (the benchmark Canadian distribution system model) of 9 bus which is adequately connected to DGs within the microgrid. Further investigation of the proposed method has been carried out for three configurations i.e grid connected, islanded and dual. It is observed from the simulation results that the operating times of relays in the grid connected configuration are similar to the operating times of the relays in the islanded mode when the optimal settings are done for the dual configuration mode and the optimizer is unable to find out any setting for both configurations without the help of FCL in the incoming feeder within the given range of relay settings.

List of Abbreviations

FCL	Fault Current Limiter
DOCR	Directional Overcurrent Relay
DG	Distributed Generation
TMS	Time Multiplier Setting
EA	Evolutionary Algorithm
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
TLBO	Teaching Learning Based Optimization
DE	Differential Evolutionary
TDS	Time Differential Setting
PMS	Plug Multiplier Setting

Keywords: Fault Current Limiter, Microgrid, Evolutionary Algorithm, Distributed Generation.

1 Introduction

The electric Power system is a large and complex system made of inter-connected equipment. It is available to the user instantly and accurately and this is possible due to a complex performance of the electric grid based on proper planning, understanding, design, installation, operation and maintenance of each of the equipment in the grid. This power grid is subjected to constant perturbations and failures like load fluctuations, faults occurring at the generator, transmission or the load end along with the occasional equipment failure. Inspite of the various fluctuations and perturbations, the power grid maintains its quasi-static state mainly due to the fact that it is supported by the huge size of connected generators and loads and the quick and remedial action taken by the protection system of the grid [1]. The response time required to take such corrective actions is in milliseconds and as human intervention is not possible, relaying is an important aspect of power system engineering. The protection system at the macro (grid level) as well as the equipment level works on the principles of correct identification of the fault, quick response and action that leads to minimum disturbance of the system. Backup protection is an inherent feature in the protection scheme to take into consideration the failure of the main protective gear. Protection coordination in general refers to the protective device coordination in the system. It is essential in the situation where more than one protective device has been installed in series between the fault point and the power supply [2]. Proper coordination ensures that protection device nearest to the fault operates first and the remaining or the backup device operates only if the primary has failed to operate and isolate the fault. To achieve this kind of selective coordination in an overcurrent protection relay based scenario, the devices have to be set based on the comparisons of the operating times of the various relays in response to the various levels of fault currents. Bad coordination will lead to wrong operation of relays during fault or overload conditions which will in turn lead to service to non-faulty parts of the grid being unnecessarily disconnected. Maloperation of relays in stressed conditions can lead to cascading trips and black-outs.

Genetic Algorithm (GA) has been used in [3] to obtain the relay settings and capacity of fault current limiter (FCL) so that the protection coordination is applicable to both the grid connected mode as well as the islanded mode of operation in the event that the incoming feeders from the transmission lines trip due to a fault on their side [3]. Research has also been done in [4] to obtain the impact of distributed generation (DG) on distribution system and the need for relay coordination is eliminated by the use of hybrid protection system based on FCL & microprocessor based overcurrent relays. Total operating time is minimized by determining time differential setting (TDS) and plug setting (PS) of all overcurrent relays of a distribution system with DG feeders using superconducting type of FCL. Selective replacement by microprocessor based relay is carried out in this case [4]. Implementation of a fault current limiter (FCL) to locally limit the DG fault current for restoring the original relay coordination in looped protective distribution system (PDS) has been carried out in [5] and it is noticed that relay coordination restoration is allowed while maintaining DG in the PDS during fault and without altering existing relay setting [5]. Research has also been carried out to determine optimum numbers and locations for FCL placement in terms of installing smallest FCL parameters to restrain short-circuit currents under circuit breakers' interrupting ratings [6]. A variety of optimization tools have been used for various research to obtain the popular objective function of the total operating time of primary and backup relays of the test system. Teaching learning based optimization (TLBO) based relay coordination has been carried out in [7] for 3 bus, 4 bus and 6 bus systems taking into consideration coordination time interval (CTI) constraints and weighing factor. Optimal coordination of directional overcurrent relays by using genetic algorithm has been carried out for a seven bus ring distribution system in [8]. The impact of DG on protection coordination has been studied and observed that conventional synchronous generator (CSG) can have an impact whereas the inverter based DGs tend to have lesser impact [9]. FCLs have been proposed as a tool to mitigate the impact of short circuit currents flowing into the microgrid in [10].

In the event of fault in the network having multiple sources, the fault current and the load current can flow in any direction. With the known characteristic of the relays, the operating sequence can be pre-determined and hence can be coordinated. The non-directional relay would need coordination from both the remote end of line and behind them. However, the directional relays would operate only in one direction and hence avoid complex coordination. Thus directional overcurrent relays (DOCR) are a good and economic protection option for the transmission and distribution system. DOCRs has two settings – Time Multiplier settings (TMS) and Pickup current settings (Iset) In general practice, these two settings are determined by two different approaches – conventional approach and optimization techniques. The Intelligence based optimization technique of DOCRs coordination simplifies the conventional approach by use of various optimization algorithms like evolutionary algorithm (EA), genetic algorithm (GA), particle swarm optimization (PSO) algorithms, Teaching–Learning-Based Optimization (TLBO) algorithm etc.

This paper is organized as follows: Section-2 illustrates the different optimization algorithms like Differential Evolutionary and teaching learning based. Section-3 describes the Microgrid concept, its structure and impact of DGs in microgrid. Section-4 discusses about the coordination in microgrid using fault current limiters where the implementation of differential evolution and teaching learning based optimization method in microgrid coordination is also presented . Section-5 focuses on the simulation results and verification of the simulation results has been reported in Section-6. Section-7 concludes this entire work.

2 Different Optimization Algorithm

Optimization is an accepted tool for problem solving based on constraints in areas of Power systems and helps in planning optimally for the generation, transmission and distribution investments and one of the applications has also been in power system protection. In this paper various optimization tools have been used to find the optimal settings of protective devices in a system which is discussed below.

2.1 Differential Evolutionary Algorithm

Differential Evolution (DE) is a stochastic, population based, evolutionary search algorithm with attributes of being simple, fast and robust. This new algorithm is proposed in [11] and it was based on creating new offspring from parent chromosome instead of the crossover or mutation. DE starts with population size NP D dimensional search variable vectors. In Equation (1) x is a variable or agent. The subsequent generations in DE are represented by the discrete time steps like t = 0, 1, 2, . . . etc. So, to represent the i^{th} vector of the generation at time t is represented as:

$$\overrightarrow{X_i}\left(t\right) = \left[x_{i,1}\left(t\right),\ x_{i,2}\left(t\right),\ x_{i,3}\left(t\right),\ldots\ x_{i,D}\left(t\right)\right] \quad (1)$$

Range is defined for each search variable and better results are obtained if the parameter lies within the range. At $t = 0$, the parameters are initialized within their range and hence the j^{th} component of the i^{th} population is initialized as below:

$$x_{i.j}\left(0\right) = x_j^L + rand\ \left(0,1\right)\ .\ \left(x_j^U - x_j^L\right) \quad (2)$$

Hereafter a donor vector is created by various methods in each generation i.e. in each population to change each member of the population. In the DE/ rand/ 1 scheme, to create the V_i vector, three random vectors are chosen from the population and a scalar factor F scales the difference between any two of these numbers and creates the vector accordingly.

Then to increase the potential diversity of the population, crossover technique is used.

2.2 Teaching Learning Based Optimization Algorithm

The Teacher Learner Based Optimization (TLBO) is a population based heuristic algorithm designed to obtain the global solution. It has been used in this paper to find the optimal solution to the coordination of over current relays and for this the optimal size of fault current limiters to be used in the models considered.

The TLBO algorithm was proposed in [12]. Like other nature inspired optimization methods listed above, this is also a population based method. The algorithm take cognizance of two methods of learning within a classroom- the first is through the interaction between the teacher and the learner – called the teacher phase and the other way is through interaction amongst the learners, which is called the learner phase. The population in this algorithm is considered to be the number of students (or learners) in the class and the different constraints considered as different subjects taught to the class. The best learner in the class is considered as the teacher of the class or the population and the results of the learner are considered as the fitness value of the problem.

The teacher is a highly learned and skilled person who shares his knowledge with the learners. He influences the learners' output in a class; in terms of results or grades of the learners. Thus his quality has a direct impact on the outcome of learners' grades. In the algorithm, he is considered as the best solution obtained so far. However, he cannot bring the learner to his level of knowledge but he moves the mean up to a certain level based on learner's capability. In the Learner phase, the learners improve their learning and their grades, through input from the teacher and interaction between themselves. Such interactions are random but a learner learns something new if the other learner has more or new knowledge than him. The flowchart is indicated in Figure 1. The different design variables will be analogous to different subjects offered to learners and the learners' result is analogous to the 'fitness', as in other population based optimization techniques. The convergence of TLBO as generation increases is indicated in the Figure 2 below.

3 Microgrid Concept

A typical microgrid structure is an aggregation of loads and microsources, operating as a single system providing power and heat as shown in Figure 3 [13]. A majority of the microsources is power electronics based to ensure controlled operation for reliability and security of the microgrid. The key issues that are part of the microgrid structure are interface, control and protection requirements of the microsources, voltage control, power flow control, load sharing during islanding and overall protection, stability and operation. Smooth transitioning from the islanded to the connected state and back is also a key feature. The microsources can be fuel cells or microturbines

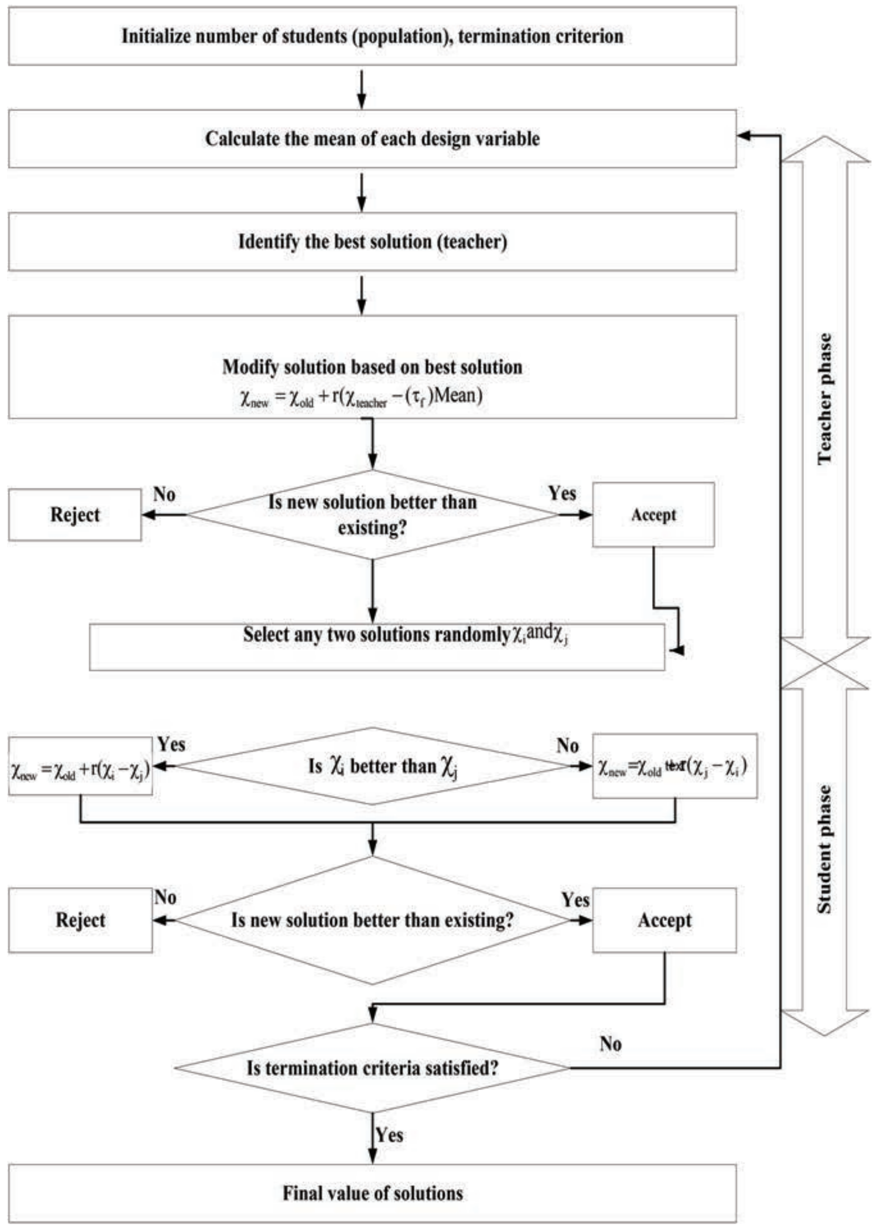

Figure 1 TLBO Flowchart.

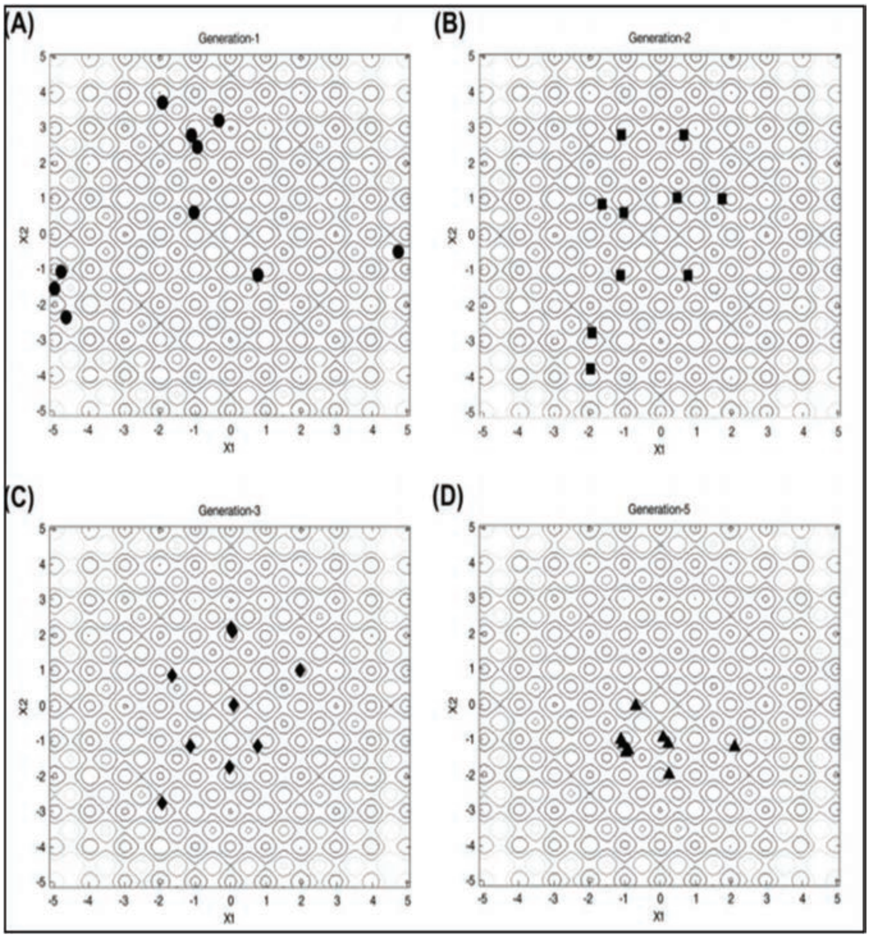

Figure 2 Convergence chart of TLBO.

and the point of coupling is the primary side of the utility transformer which defines the separation between grid and microgrid. The placement of the microsources on the feeders can be as per a wide range of options and may depend upon requirement to reduce line losses or to support the voltage of the feeder.

In the event of a failure or fault in the distribution system, the microgrids are automatically invoked to ensure that the consumers within the microgrid have continued service. This benefit however comes with the additional complications in the protection system which has to deal with the microgrid

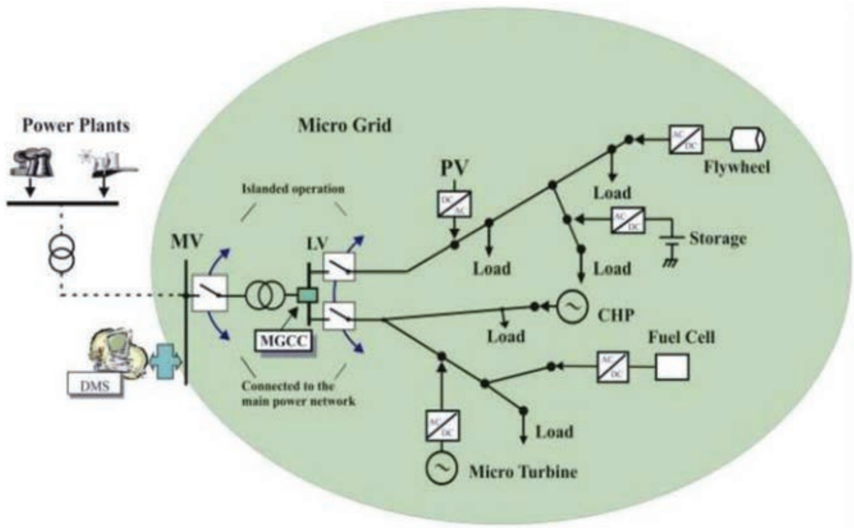

Figure 3 Configuration of Microgrid.

Legends: DMS-Distribution Management System, MGCC-Microgrid system central controller, CHP-Combined heat and power, MV-Medium voltage substation microgrid, PV-Photo Voltaic

being supplied by the main grid as well as the scenario in which the microgrid is supplied by its distributed generation within the system. In general the microgrid is interfaced to the main grid through a semiconductor switch called the 'Static Switch' [14]. This switch autonomously islands the microgrid during disturbance and reconnects it to the main system again autonomously, after the cause of the tripping or switching is not available anymore and is required to open at all fault conditions.

3.1 Distributed Generations in MicroGrid

Distributed Generations are small generating units which may utilize new or modified technology. They are mostly installed near loads and can be owned by utilities, consumers or Independent Power Producers (IPPs). It has become a significant phenomenon in power systems and its capacity can range from 1 KW of PV installation to 1 MW of engine generators to 1000 MW from offshore wind farms [15]. They act as supplement to the utility system at mostly the medium and low voltage grid levels. The benefits are

- Improved power quality and voltage support
- Loss reduction
- Transmission & distribution capacity release
- Deferments of new or upgraded transmission & distribution infrastructure
- Improved utility system reliability

The challenges due to increased penetration of DG include voltage rise effect (which limits the amount of DG capacity that can be connected to the distribution network), the power quality aspects (transient voltage variations and harmonic distortion of voltage), protection of the system from faults and islanding issues, their impact on the network stability and security etc. Hence there is a thought that active distribution management efforts are required to operate such microgrids. A proper dynamic model of the DG can give an idea about its behavior in the system and the synchronous type DGs can be modeled as per the conventional methods.

The presence of DGs impacts the grid in both ways. The presence of DG has the potential to change the quantity and direction of the short circuit current that may flow at a point during normal as well as fault conditions. This leads to loss in protection coordination and the total relay coordination of this part of the distributed system or microgrid needs to be redone to ensure that mal-operation of relays do not happen and adequate tripping of relays take place in the event of fault. This is a very tedious and time taking task for the grid engineer. This impact of the DG depends upon the size, location, technology and method of interconnection of the DG to the distribution system. This impact on the protection of the microgrid leads to the system operator disconnecting DGs during faults within the microgrid so that the original setting of relays is applicable and useful to clear the faults. This leads to loss of power from the DGs and the effort of resynchronizing the DGs after clearing the fault [5]. Also since the transmission end faults can lead to outage of the grid connected feeders and if the microgrid switches seamlessly from the grid connected to the islanded mode, the relays should be able to be effectively save the system if a fault occurs within the microgrid while its being islanded- so the same relay coordination should be applicable for both instances. For distribution systems without DGs, relay coordination can be done by breaking the system into loops and then coordinate the breakpoint for both directions [16]. Linear graph theory can be used to find the breakpoint set and various optimization methods can be used to minimize the objective function which mostly is the minimization of relay operating times during severe fault conditions. Adaptive methods for protection coordination are also done.

4 Coordination in Microgrid Using Fault Current Limiter

Fault Current limiters provide a good solution to the problem of very high short circuit currents in the grid or industrial system. They are a supporting technology in the concept of the smart grid. With current limiters the utility can provide a stiff power system with low impedance and low fault current levels. Most of the research work in the relay coordination assumes a fixed network topology. However in reality, with regard to a single contingency there are multiple topologies due to various occurring system contingencies and operating conditions. Thus the protective system will operate without selectivity and hence there is a need to incorporate the effect of all such coordination constraints while solving the coordination problem. These coordination constraints are a set of nonlinear inequality constraint corresponding to each network topology. In the event of a fault in a properly coordinated system, the primary relay should trip to isolate the faulty section. In case of the failure of the primary relay, its corresponding back-up relay should trip to achieve isolation of the fault. In reality, based on the location and level of faults, few non-primary and non-backup relays may operate for a fault. Such unwanted trip removes additional operational circuit along with the faulted circuits, thus decreasing the reliability of the power system.

The operating time of the overcurrent relay (OCR) depends upon the fault current flowing through it and its exclusive settings of Time multiplier (TMS) and Pickup current settings (I_p). The I_p is the minimum value of current above which the relay starts to operate. The time delay and pickup current parameters are independent of each other in the overcurrent relay. Directional element for overcurrent relaying is a necessity to obtain selectivity in multiple source circuits. For the inverse characteristic of the overcurrent relay considered in this work, the operating time is given by:

$$t = TDS \frac{A}{\left(\frac{I_{sc}}{I_p}\right)^B - 1} \tag{3}$$

The constants A and B vary for different characteristic of OCRs and for the minimum time inverse characteristic type OCR, the value of A is 0.14 and B is 0.02. The objective function is to minimize the operating times calculated for every primary and backup relay for every fault case. This also includes the relay operating times for both configurations of the microgrid- that is the grid connected mode and the islanded mode of operation.

$$Minimize\,T = \sum_{c=1}^{C}\sum_{i=1}^{N}\sum_{j=1}^{M}\left(t^{p} + \sum_{k=1}^{K} t^{b_k}\right) \tag{4}$$

The above objective function is modified accordingly to suit the various scenarios that are being considered for the study. The above however represents the final scenario that finds the optimal settings of FCL and all the relays in both modes of operation of the microgrid. For the above formulation, C stands for the two configurations to be considered, N stands for the number of fault nodes or cases to be considered and M is equal to the number of primary and backup relays identified for each of the fault condition. The elements within the brackets signify the primary and backup relays considered for each fault. Enumerating the constraints within which the results have to be obtained: The maximum and minimum values of the I_p and TMS needs to be provided to the optimizer to ensure that the outputs can be set onto the OCR. The range of settings for the relays can therefore be defined as below:

$$I_{p_i-min} \leq I_{p_i} \leq I_{p_i-max}\,, \qquad \forall i \tag{5}$$

$$TDS_{i-min} \leq TDS_i \;\leq TDS_{i-max}\,, \qquad \forall i \tag{6}$$

Similarly, the limit to the size of FCL that can be installed at the grid infeed end of the microgrid has to be defined to ensure that the optimal value is obtained.

$$0 \leq \; X_{FCL} \; \leq \; X_{FCL_{max}} \tag{7}$$

One of the important criteria of protection coordination is to ensure that the backup relays operate after the primary relays. To further ensure that maloperation due to this aspect does not occur, a minimum CTI (Coordination Time Interval) is kept between the operating times of primary and its backup relay. In this case the CTI has been kept at 0.2 seconds. This time interval ensures that the relay and circuit breaker operating times of the primary relays are taken care of during protection coordination and backup relays do not race to operate during the period when the primary relays are clearing the faults.

$$t_{cij}^{b_k} - \; t_{cij}^{p} \; \geq CTI \qquad \forall\, c, i,\; \{j,\; k\} \tag{8}$$

In this problem, the active inductive FCLs are switched into the circuit when the faults occur. This leads to change in the Ybus and Zbus matrix since the Xfcl merges with the Z bus matrix during fault. Such complicated scenarios can only be determined by heuristic optimizer.

4.1 TLBO & DE Optimization Method Implementation in Coordination of Microgrid

The teaching-learning based optimization and Differential Evolution methods have been taken for the purpose of obtaining the solution of the relay settings and the fault current limiter settings in both the test systems. In each of the relays, the time multiplier setting (TMS) and the plug setting (Ip) need to be determined. Therefore if a system has N relays and M number of FCLs, the objective of the programme would be to find out 2N+M values from the optimizer. This corresponds to 43 dimensions in the 9 bus system. The population taken therefore comprises of number of individuals as decided by the input and each individual is a string of the appropriate dimension as above. To satisfy the various scenarios which have been enumerated in the previous section, the constraints are modified as per the operating conditions and optimal numbers of generations of the populations are taken to ensure that the results of the optimizer are acceptable. The FCL values are also obtained from the optimizer and the presence of the FCL is implemented only in short circuit calculations that have the grid connected feeder, i.e. the grid connected mode. Further in the situation when the microgrid is islanded, the FCL does not figure in the test case. In the grid connected mode, in the presence of FCL, the Ybus of the system is different from the Ybus of the islanded microgrid. Fault currents against each relay for every fault location are found out.

In this work, the objective function of the optimizer seeks to find the sum of operating times of the primary and backup relays for the successive faults carried out at each of the fault nodes, i.e. nodes 10–17 in 9 bus system. In addition to the sum of the operating times of the considered relays, the objective function also considers the penalty values which are caused due to one or more constraints becoming binding. One of the constraints that have to be considered is the CTI constraints. The difference in time of operation of the primary and its backup relay has been kept to a minimum value of 0.2 seconds in this case to ensure that maloperation of backup or unnecessary opening of unfaulted lines do not occur before the operation of primary relays. The fault considered in the short circuit analysis is the three phase short circuit to ground fault at each of the fault nodes. This is to ensure that one of the worst case scenarios is considered for relay coordination problem and the capability of the FCL to be installed. Program flowchart of the proposed method is shown in Figure 4.

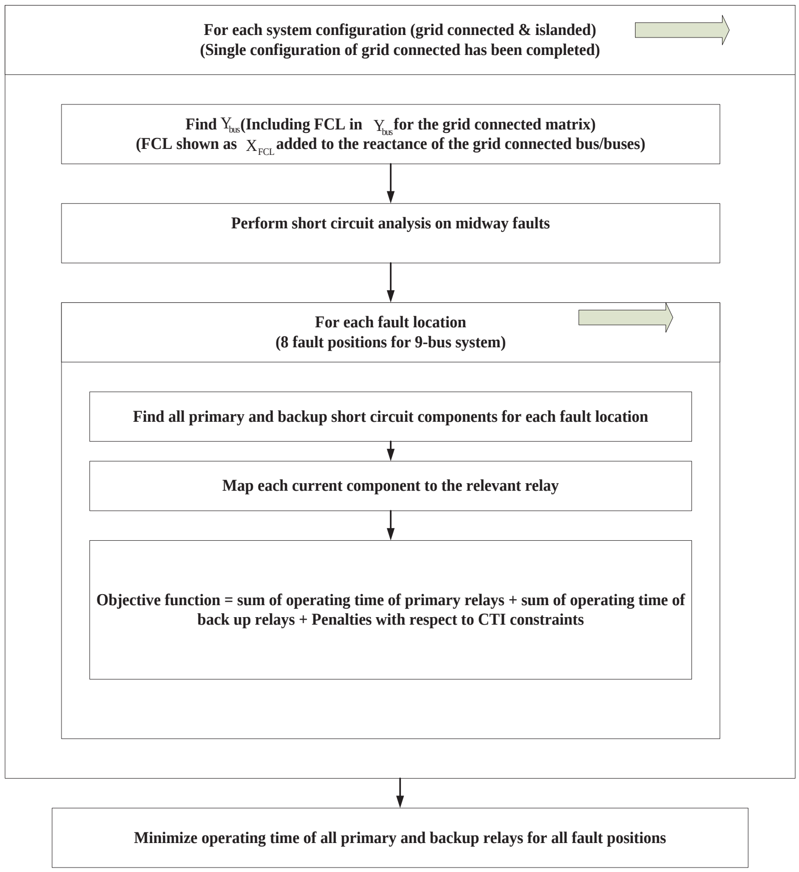

Figure 4 Programme Flowchart.

5 Simulation Result Analysis

The proposed solution is tested on a radial distribution system (the benchmark Canadian distribution system model) of 9 bus which is adequately connected to DGs within the microgrid. The detailed discussion is given below:

5.1 Case Study of 9 Bus Canadian Urban Benchmark Distribution System

In this system as shown in Figure 5, two feeders rated 8.7 MVA, and impedance 0.1529+j.1046 ohms/km is fed by a utility of short circuit ratio 500 MVA and X/R ratio = 6. The distribution transformer is 115KV/12.47 KV. To convert

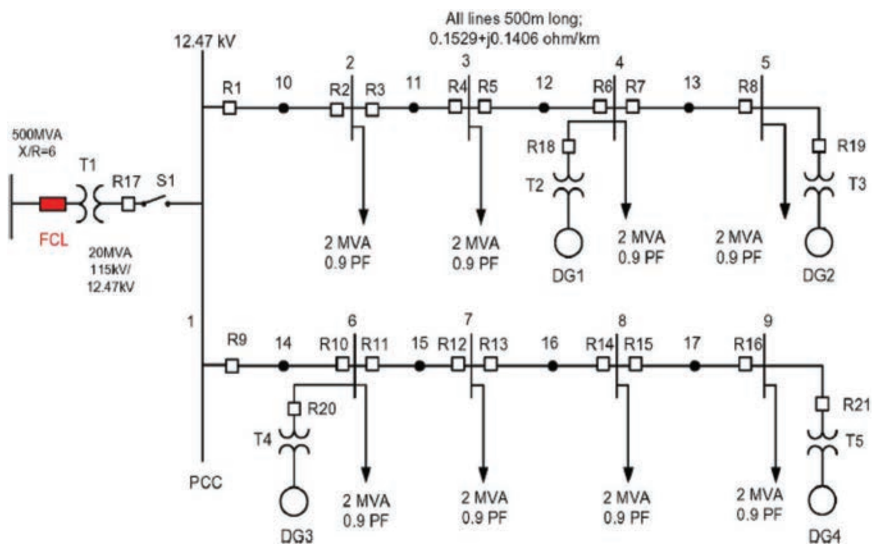

Figure 5 9-Bus Model.

Legends: PCC-Point of Common Coupling, R-Relay, PF-Power Factor, DG-Distributed generator

this radial system into a microgrid, four nos of Distributed generation of conventional type have been connected to the buses 4, 5, 6 and 9.

The DGs are connected to the buses through 12.47 KV/480 V transformers and the rating tested is 5 MVA each with similar characteristics. The loads are rated loads of 2 MVA each at 0.9 PF which are connected at all buses from 2 to 9. There are directional overcurrent relays installed at both ends of the lines and the total numbers of such relays are 17. They are required to operate for both primary and backup line faults. Faults are programmed for occurring on the midpoint of the line sections and the primary and backup relays are mapped out for each of the fault scenario. Accordingly eight additional nodes are introduced in the system and short circuit analysis is carried out. Since the system has multiple sources of generation, fault currents shall flow from both ends of the line into the fault. For each fault at the midpoint, there are two primary relays at both ends of the lines and depending on the direction of the fault current flow, backup relays are obtained. The number of backup relays against each primary relay has been restricted to two. For example, in case of a fault at node 14, the primary relays are 9 and 10 and the backup relays considered for R9 are R2 and R17 and for R10 are R12 and R20. Three phase

Table 1 Primary and Backup Relay in 9 Bus Model

Fault Locations at Bus #	P	b1	b2
10	1	10	17
10	2	4	
11	3	1	
11	4	6	
12	5	3	
12	6	8	18
13	7	5	18
13	8	19	
14	9	2	17
14	10	12	20
15	11	9	20
15	12	14	
16	13	11	
16	14	16	
17	15	13	
17	16	21	

short circuit faults are created at each of the nodes 10 to 17 and operating times of Directional overcurrent relay (DOCRs) is obtained. The details of primary and backup relays are provided in Table 1 below.

Studies have been done to find the relay settings and the value of the Fault current limiters that should be required for the systems to operate seamlessly in both the configurations under symmetrical three phase faults –

- Grid connected mode – when the microgrid is being supplied by the grid connected feeders as well as the Distributed generation
- Islanded mode – when the grid connected feeder is absent and the loads within the microgrid are being supplied by the distributed generation.

Here three phase faults have been considered for protection coordination.

5.2 Grid Connected Configuration

In this case, the test system has no fault current limiters (FCLs) but has grid and all DGs connected to the system. The fault currents applicable are obtained from standard available MATLAB programs. This system now operates as a multisource microgrid with fault currents being available from both ends of each faulted line in the case of the 9 bus. For this problem, the fault currents are not unidirectional and hence a simple optimization problem is made to get the optimal settings of all relays and the fault currents at each relay point.

Optimal values of relay settings for grid connected mode are obtained and is shown in Table 2. In Table 2, TDS is time dial setting.

5.3 Islanded Configuration

In this case the grid is absent and the microgrid is fed by the DGs only. The settings are obtained for the test system in the islanded mode. Relay settings thus obtained are those which would be providing good protection coordination in the islanded microgrid in case of the disconnection of the transmission side grid in the event of fault on the transmission side. Optimal settings of relays are obtained for the islanded system fed by DGs and shown in Table 3.

Table 2 Optimized Relay setting for 9 Bus Grid connected mode (without FCL)

Relay	TDS(*s*)	I_p(*pu*)	Relay	TDS(*s*)	I_p(*pu*)
1	0.230	0.650	12	0.351	0.178
2	0.204	0.650	13	0.297	0.001
3	0.224	0.209	14	0.292	0.396
4	0.258	0.650	15	0.010	0.001
5	0.132	0.112	16	0.302	0.489
6	0.283	0.650	17	0.500	0.078
7	0.010	0.001	18	0.397	0.239
8	0.392	0.240	19	0.316	0.495
9	0.229	0.650	20	0.198	0.560
10	0.300	0.290	21	0.367	0.451
11	0.166	0.650			
			Tops	28.9	

Table 3 Optimized Relay setting for 9-Bus in Islanded Mode

Relay	TDS(*s*)	I_p(*pu*)	Relay	TDS(*s*)	I_p(*pu*)
1	0.262	0.210	12	0.307	0.136
2	0.261	0.498	13	0.135	0.109
3	0.145	0.340	14	0.338	0.199
4	0.338	0.453	15	0.011	0.334
5	0.160	0.024	16	0.313	0.355
6	0.466	0.320	17	0.398	0.396
7	0.010	0.001	18	0.332	0.461
8	0.327	0.461	19	0.375	0.463
9	0.192	0.530	20	0.235	0.384
10	0.196	0.65	21	0.292	0.529
11	0.306	0.05			
			Tops	27.855	

Table 4 Optimized relay setting for 9 Bus in Dual configuration mode with FCL

Relay	TDS(s)	$I_P(pu)$	Relay	TDS(s)	$I_P(pu)$
1	0.320	0.255	12	0.481	0.072
2	0.290	0.355	13	0.068	0.041
3	0.160	0.309	14	0.291	0.474
4	0.279	0.386	15	0.012	0.051
5	0.155	0.033	16	0.482	0.045
6	0.463	0.390	17	0.160	0.092
7	0.012	0.273	18	0.498	0.139
8	0.357	0.274	19	0.432	0.137
9	0.219	0.429	20	0.366	0.282
10	0.246	0.362	21	0.448	0.390
11	0.138	0.155			
	Xfcl			1.952	
	Total Tops			**65.36**	

5.4 Dual Configuration Mode

In this case the test system takes into consideration both the above modes of operation. The final objective of the present work is achieved by finding out the various settings of relays as well as the fault current limiter values such that the same set of settings are applicable to protect the microgrid in both configurations.

Optimal results in Table 4 obtained show that the values of FCL are significant. This is consistent with the results in works available in literature and is due to the fact that the value of FCL should be capable to suppress the short circuit values. The settings of DOCRs have also changed substantially. Table 5 shows that some of the CTIs for grid connected mode are greater than 0.2.

Table 6 shows that some of the CTIs for islanded connected mode are greater than 0.2.

5.5 Maloperation in Absence of Optimal Setting

In this section the behavior of system is observed after application of incorrect relay settings. Here relay settings obtained on the basis of grid connected mode is used in the situation when the microgrid is operating in islanded mode. Relay settings applicable for plain grid connected mode is used for detecting maloperation of relays when the system is operating in islanded mode and fault occurs. Random relays are highlighted in Table 7 which have operating times lesser than the primary relays of the corresponding fault location, thus showing failed relay coordination.

Table 5 CTI Analysis in 9 Bus for final optimal settings – Grid Connected

Fault Location	p_Primary	P_tops	b1_Primary	b1_Tops	b2_Primary	b2_Tops	CTI1	CTI2
1	1	0.601	10	0.827	17	0.807	0.2	0.2
1	2	0.786	4	0.990		0.000	0.2	0.0
2	3	0.409	1	0.610		0.000	0.2	0.0
2	4	0.965	6	1.166		0.000	0.2	0.0
3	5	0.217	3	0.417		0.000	0.2	0.0
3	6	1.146	8	1.347	18	1.348	0.2	0.2
4	7	0.012	5	0.220	18	1.366	0.2	**1.4**
4	8	1.321	19	1.526		0.000	0.2	0.0
5	9	0.577	2	0.803	17	0.813	0.2	0.2
5	10	0.806	12	1.035	20	1.543	0.2	**0.7**
6	11	0.391	9	0.592	20	1.562	0.2	**1.2**
6	12	1.023	14	1.337		0.000	0.3	0.0
7	13	0.202	11	0.404		0.000	0.2	0.0
7	14	1.315	16	1.517		0.000	0.2	0.0
8	15	0.008	13	0.209		0.000	0.2	0.0
8	16	1.500	21	1.711		0.000	0.2	0.0

Table 6 CTI Analysis in 9 Bus for final optimal settings – Islanded Mode

Fault Location	p_Primary	P_tops	b1_Primary	b1_Tops	b2_Primary	b2_Tops	CTI1	CTI2
1	1	0.617	10	0.824	17	0.000	0.2	0.0
1	2	0.786	4	0.99		0.000	0.2	0.0
2	3	0.423	1	0.626		0.000	0.2	0.0
2	4	0.965	6	1.166		0.000	0.2	0.0
3	5	0.221	3	0.431		0.000	0.2	0.0
3	6	1.146	8	1.347	18	1.348	0.2	0.2
4	7	0.012	5	0.224	18	1.365	0.2	**1.4**
4	8	1.321	19	1.526		0.000	0.2	0.0
5	9	0.601	2	0.802	17	0.000	0.2	0.0
5	10	0.805	12	1.035	20	1.535	0.2	**0.7**
6	11	0.401	9	0.615	20	1.553	0.2	**1.2**
6	12	1.023	14	1.337		0.000	**0.3**	0.0
7	13	0.207	11	0.414		0.000	0.2	0.0
7	14	1.315	16	1.517		0.000	0.2	0.0
8	15	0.008	13	0.214		0.000	0.2	0.0
8	16	1.500	21	1.711		0.000	0.2	0.0

Table 7 Maloperation of relays in 9-Bus

Fault location \ Relays	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.81	0.72	0.00	0.92	0.00	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.83	0.00	0.50	0.90	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.51	0.00	0.24	0.96	0.00	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.25	0.00	0.01	1.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18	1.35	0.00	0.00
5	0.00	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.73	0.00	0.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	0.00	0.49	0.91	0.00	1.11	0.00	0.00	0.00	0.00	0.00	0.93	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.22	1.10	0.00	1.30	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	0.01	1.28	0.00	0.00	0.00	0.00	1.48

6 Verification of Simulation Results

Fault currents as seen by relays have been verified by the ETAP model. Fault currents available in the short circuit report match with the values obtained by the MATLAB program as shown in Figure 6.

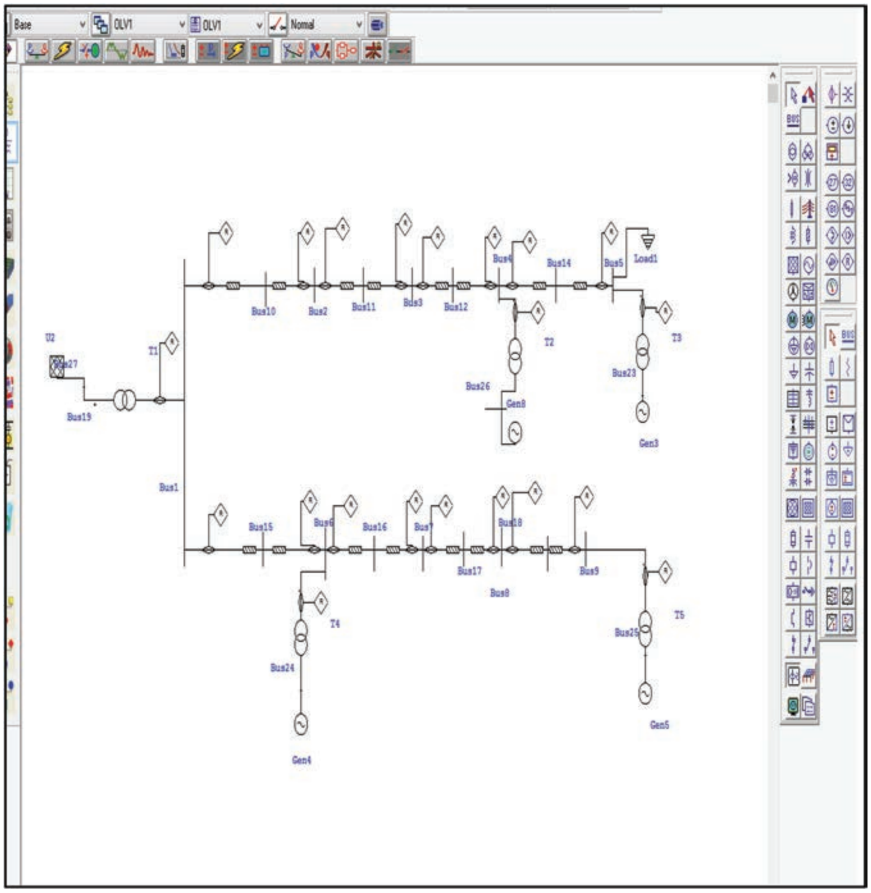

Figure 6 Etap model for 9 bus system.

7 Conclusion

The need for reliable, quality and uninterrupted power is one of the major reasons behind the increasing popularity of the concept of the microgrid and its use in the modern grid is here to stay as the utilities, manufacturers and regulators are increasingly investing into the idea. The planning, operation and protection of such microgrids is therefore becoming important and research is being done to find varied methods to do so- the operational and financial aspects can therefore be looked into for each solution of the problem in operation and protection of the microgrid. Such power delivery systems or microgrids frequently have inverse time overcurrent relays of the directional type [5]. In this paper protection coordination problem formulation is modified to take into consideration the microgrid protection settings which can be applicable for both the islanding and the grid connected mode of operation. This work uses the FCL to reduce the short circuit currents to an optimal levels such that the protection coordination can be applicable for both the configurations of the grid connected microgrid as well as the islanded mode operation of the microgrid. This is done by considering reactive FCLs only and optimization programme is run considering both the cases simultaneously with the FCL applicable in the grid connected mode only. The Y bus matrix changes continuously with every value of the FCL. The values of FCLs have been calculated for a radial type system and it is observed that the capacity of FCL depends upon the size and complexity of the system. It is also observed that the standard relay settings take into consideration only the grid connected mode of operation and do not work for the islanded mode of operation. The consequent maloperation of relays in the adjacent feeder of the radial type system in the 9 bus Canadian benchmark system is presented in the work. It is also observed that the operating times of relays in the grid connected configuration are similar to the operating times of relays in the islanded mode when the optimal settings are done for the dual configuration mode. It indicates that the fault current levels for both the systems have been made similar due to the use of FCLs. It is also observed that the optimizer is unable to find out any setting for both configurations (grid and islanded) without the help of FCL in the incoming feeder within the given range of relay settings.

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