Optimal Relay Coordination for Microgrids Using Hybrid Modified Particle Swarm Optimization - Interval Linear Programming Approach

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***Abstract*—In practical power systems, the fault current sensed by the relay depends on location of the fault and network topological changes. Fault current sensed by the relay for near end fault is greater than that for a far end fault. In meshed distribution systems with Distribution Generation (DG), the fault currents are fed from both ends of the line and consequently the currents sensed by the relays at both ends are different. These variable fault currents may lead to miscoordination of directional overcurrent relays (DOCRs). To overcome this problem, the coordination constraints corresponding to the fault currents at different fault locations should be satisfied. This paper proposes a new approach based on Interval Linear Programming (ILP) which is hybridized with Modified Particle Swarm Optimization (MPSO). The basic idea is to convert the inequality constraints of a standard linear programming (LP) problem to interval constraints using theory of ILP and represent the ILP problem as a standard LP problem. This procedure reduces considerable number of coordination constraints and better sub-optimal solution is obtained compared to conventional optimization. The proposed method is tested on IEEE 14 bus test system in microgrid perspective.**

***Index Terms*—Optimal relay coordination, microgrids, modified particle swarm optimization , interval linear programming, directional overcurrent relays, nonlinear optimization.**

I. INTRODUCTION

Increasing concerns of global warming due to extensive burning of fossil fuels encouraged utilization of renewable energy generated at the consumer end using Distributed Generation (DG). This resulted in autonomous operation of distribution system which accommodates both loads and generation side-by-side with or without relying on the main power system. Such autonomous distribution systems are called microgrids. Despite having the advantages of autonomous control, efficient usage of low voltage renewable power generation microgrid operation makes the system protection complex. Because, existence of DGs in distribution side vary the magnitude and direction of short circuit currents. Change in network topology including addition of DG or change in the operating mode of Microgrid from grid connected mode to isolated mode change the magnitude and direction of currents.

The relay coordination problem, which is a part of protection planning, has been an active research problem in power transmission and distribution systems. Extensive research is under progress on protection coordination problem for the past few decades. Trial - error method and topological methods are used in initial days for protection coordination. After the advent, numerical optimization techniques were widely used and chosen as primal choice by the research engineers in obtaining solution to relay coordination problem. Objective function is formulated by minimizing the overall operating time subjected to certain limit and coordination constraints. Linear Programming techniques [1]-[3] like Simplex, dual Simplex etc., and nonlinear programming techniques like MINLP [4] have been applied to find the optimal relay settings. Also, in recent past natural inspired optimization algorithms like Evolutionary Programming (EP), Genetic Algorithms (GA) [5]-[6], Differential Evolution [7] etc., have also been used in solving the optimal relay coordination problem.[8],[9] have reported a hybrid GA optimization technique which utilizes the advantages of both GA and conventional optimization techniques like LP and NLP to find better optimum. In microgrids, different DGs contribute to different fault current magnitudes. In recent past interval analysis techniques are widely used in power system applications like power flow analysis [10], optimization in electricity markets and fault location detection [11,12]. [13] implemented ILP for relay coordination problem for various network topologies. Modified particle swarm optimizers for optimal relay coordination are proposed in [14-15]. [17] proposed a hybrid particle swarm optimization approach to relay coordination in microgrid scenario. This paper introduces a hybrid MPSO - ILP method in which pickup current settings are optimally found by MPSO and time settings are calculated using ILP approach subjected to limit and coordination constraints. The relay coordination problem is formulated for microgrid system case with two network topologies i.e., grid connected and isolated modes, assuming fixed installed DGs with multiple fault current scenarios (near end, midline, far end and fault at 10% distance each on the line).

II. INTERVAL LINEAR PROGRAMMING

Many real life situations we come across are problems with imprecise variables. This imprecision or uncertainty can be modelled in various ways. One such way is representing those variables by intervals. Interval analysis is a very useful tool in representing variables which are "Uncertain but bounded". Interval arithmetic is a logical extension of conventional arithmetic defined over real intervals. Let us define two bounded intervals V and W on a real line defined as $V = [V^L, V^U] = \{v \in \Re : V^L \leq v \leq V^U\}$ and $W = [W^L, W^U] = \{w \in \Re : W^L \leq w \leq W^U\}$. Let " $\bullet$ " denote one of the operations + , - , $\div$, and $\times$ on V and W respectively. The superscripts $'U','L'$ denote upper, lower bounds of the interval and superscript $'I'$ denote the interval for a matrix or vector. The generalized arithmetic operations with bounded intervals can be represented as,

$$V \bullet W = \{v \bullet w : v \in V, w \in W\} \tag{1}$$

and the arithmetic operations are given below,

$$V + W = [v^L + w^L, v^U + w^U] \tag{2}$$

$$V - W = [v^L - w^U, v^U - w^L] \tag{3}$$

$$\begin{aligned} V \times W = \{& min(v^U w^L, v^U w^U, v^L w^L, v^L w^U), \\ & max(v^U w^L, v^U w^U, v^L w^L, v^L w^U)\} \end{aligned} \tag{4}$$

$$V \div W = [v^L, v^U][1/w^U, 1/w^L], \;\; 0 \notin W \tag{5}$$

Now, the standard ILP problem is represented by (6) and (7) as shown below:

$$min \;\; Z = (C^I) X \tag{6}$$

subjected to :

$$A^I X \leq b^I, \;\; X \geq 0 \tag{7}$$

where, C^I and A^I are the interval vector and matrix respectively. They are defined as follows:

$$C^I = [C^L, C^U], C = C : C^L \leq C \leq C^U \tag{8}$$

$$A^I = [A^L, A^U], A = A : A^L \leq A \leq A^U \tag{9}$$

The optimal solution to (6) and (7) is obtained by solving the standard LP problem [13] which is defined as,

$$min \;\; Z = (C^U or C^L) X \tag{10}$$

subjected to :

$$A^U X1 - A^L X2 \leq b^L, \;\; X1, X2 \geq 0 \tag{11}$$

and,

$$X = X1 - X2 \tag{12}$$

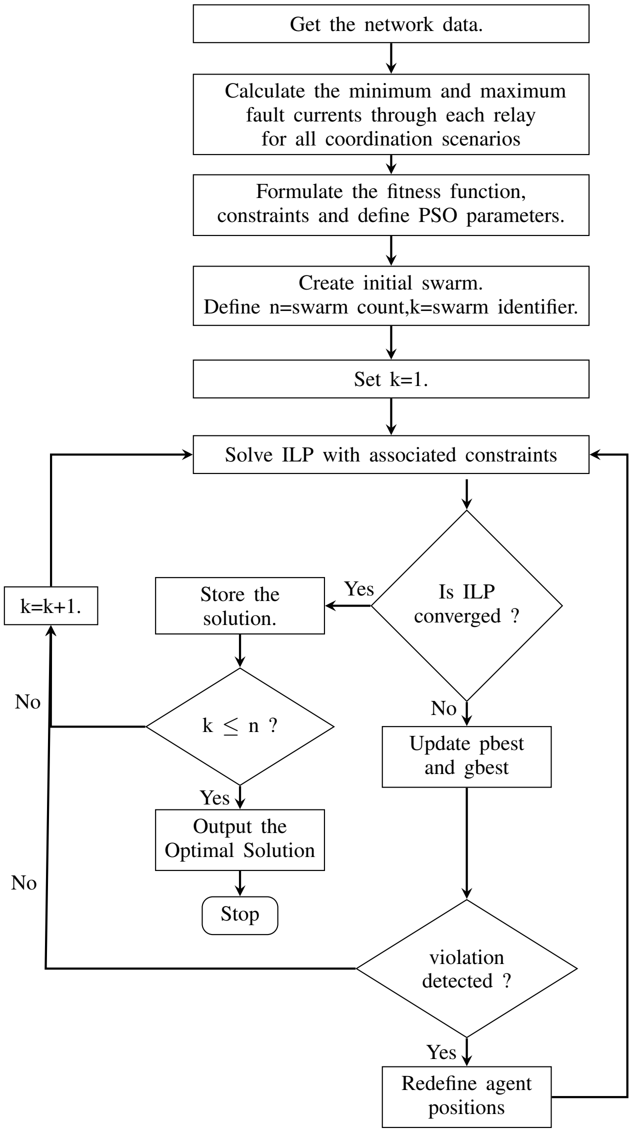

Fig. 1. Flowchart for hybrid MPSO-ILP implementation to relay coordination

III. HYBRID MPSO - ILP APPROACH

The relay coordination problem is solved by using hybrid Modified Particle Swarm Optimization-Interval Linear Programming (MPSO-ILP) Method. PSO is a population based search algorithm which is naturally inspired from socialistic behavior of bird flocking and fish schooling. As PSO is gradient independent method, like other evolutionary algorithms it can be applied to functions whose gradient is unavailable.

A. Standard Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an evolutionary search technique which maintains randomly initialized agents, called swarm. Unlike genetic algorithm, PSO doesn't kill its population, but each pupil will evolve towards the global optimum. The radomly initialized agents are spread in the entire problem search space. Each agent has memory to record its position, velocity and at all times, it maintains its best position, called personal best (pbest). In case of minimization problem, the personal best of an agent is the minimum function fitness attained by the agent in its entire journey. In a similar way the personal best for all agents is recorded and the smallest best of all personal bests is recorded as the global best (gbest). The particles of the swarm are assumed to travel in the search space in discrete time steps (assumed unity in general). In each time step the velocity and position of each particle is updated using following equations:

$$v(k+1) = w*v(k) + c_1*rand_1*(pbest_i - x(k)) + c_2*rand_2*(gbest_i - x(k)) \tag{13}$$

$$x(k+1) = x(k) + v(k+1) \tag{14}$$

where $v(k+1)$, $v(k)$ are the modified and current velocities of the agent. $rand_1$ and $rand_2$ are random numbers between 0 and 1. $pbest_i$ and $gbest_i$ are personal best and global best in i^{th} dimension. $x(k+1)$ and $x(k)$ are the modified and current position of i^{th} agent and c_1, c_2 are cognitive and social coefficients respectively. In general, the velocity of the agent is bounded by $[-v_{max}, v_{max}]$ to mitigate the possibility that the particle could fly out of the problem space. If the problem is space is also bounded by limits $[-x_{max}, x_{max}]$, then the maximum velocity of the agent is typically set to $v_{max} = k * x_{max}$. w is the inertia weight which governs the participation of past velocity to find the present velocity and position.

B. Modified Particle Swarm Optimization

Conventional standard PSO is used to solve the unconstrained optimization problems. But, for many optimization problems like relay coordination which are highly constrained, the PSO algorithm must be modified to take constraints into consideration. The modified PSO includes both initializing the agents within the feasible problem space along with considering the relay coordination constraints. The coordination constraints are included in the fitness function by including a penalty factor. For example, if the constrained optimization problem is defined as,

$$min \;\; W = g(x,y) \tag{15}$$

$$Subject\ to \;\; x \leq y \tag{16}$$

$$x\ ;\ y \geq 0 \tag{17}$$

$$min \;\; W = g(x,y) + \lambda_1 max(0,(x,y)) + \lambda_2 max(0,-x) + \lambda_3 max(0,-y) \tag{18}$$

where λ_1,λ_2 and λ_3 are the penalty factors added to increase the function fitness in case of constraint violations. In each iteration, the function fitness is evaluated and the agent position and velocity are updated according to the function fitness. If any agent is going out of bounds, that agent position is brought back to the boundary limit and the fitness is tested again. The ILP problem is defined as a subproblem to MPSO. In each iteration, the ILP is solved using the predefined values of pickup settings and coordination constraints. The iterations are stopped once all the coordination constraints are satisfied with all agent positions within limits.

IV. RELAY COORDINATION PROBLEM FORMULATION

The optimal relay coordination problem is formulated to find the optimal values of TMS and PS of Directional Overcurrent Relays (DOCRs) with an objective of minimizing the overall time of operation. From the time-current characteristics, the operating time of DOCR is given as follows:

$$t_{rf} = \frac{a(TMS_{rf})}{\left(\frac{I^F_{rf}}{PS_r}\right)^b - 1} \tag{19}$$

where, r is the relay identifier, f is the fault location identifier, a and b are constants based on the type of DOCR selected. Here a and b are taken to be 0.14 and 0.02 respectively. In (19) TMS_{rf} and PS_r are the Time Multiplier Setting (TMS) and Plug Setting (PS) of r^{th} relay for an f^{th} fault location. The objective function for the optimization problem is defined as follows:

$$min \;\; T = \sum_{m=1}^{M}\sum_{f=1}^{F}\sum_{r=1}^{R} t^p_{mfr} \quad \forall \; r \; \in \; R \tag{20}$$

where R is the set of all relays considered for coordination, F is the number of Fault locations, M is the mode of microgrid operation. The values for t_{mfr} can be obtained from equation (19). Each DOCR is operated with two settings i.e. TMS_{rf} and PS_r. Now, (19) is a nonlinear equation which can be linearized by substituting PS values. Thus, the PS values are chosen in such a way to optimally obtain the TMS values using ILP. Now, the objective function (20) is minimized by satisfying certain number of constraints which are given below,

A. Coordination Constraints

For sucessful coordination of DOCRs, the backup relay is allowed to operate only in instances where primary relay fails to operate. So, there should be a minimum time intervel for which the backup relay holds to allow the primary relay to operate. This time gap is called Coordination Time Interval (CTI). The CTI usually varies between 0.2 to 0.5. The coordination constraint is given below,

$$t_j - t_i \;\; \geq \;\; CTI \quad\; \forall \;\; (i,j) \;\; \in \;\; R \tag{21}$$

B. Bounds on operating time of the relay

The performance of the relay in terms of speed should neither be too fast nor be too slow. Hence a constraint is imposed on the relay on its operational speed which is mathematically formulated as,

$$t^{min}_r \;\; \leq \;\; t_{fr} \leq \;\; t^{max}_r \tag{22}$$

where t^{min}_r and t^{max}_r are the minimum and maximum operating times of r^{th} relay and t_{fr} is the actual operating time of r^{th} relay for f^{th} fault location.

C. Bounds on TMS and PS

The value of TMS and PS of the relay directly affect its operating time which puts bounds on their values, given by,

$$TMS^{min} \leq TMS_r \leq TMS^{max} \quad (23)$$

$$PS^{min} \leq PS_r \leq PS^{max} \quad (24)$$

(20) should be solved for various fault scenarios in grid connected and isolated modes of microgrid operation. In the present work totally 11 fault scenarios (near end, mid line, far end and 10% distant each on the line) are taken into consideration on each line in each mode of microgrid operation. Each scenario (20) is solved taking 'n' coordination constraints represented by (21). For 'F' fault locations, including 'M' operating modes, totally FxMxn constraints are to be solved. This number will further increase with number of fault scenarios and network topological changes. In total there are FxMxn number of linear constraints, each constraint of (21) is represented by FxM times with different weighting coefficients (coefficients of design variables in the objective function). So, the computation becomes tedious and redundant. To reduce the computational effort, the constraint coefficients can be represented as "uncertain but bounded" intervals and can be solved by using interval optimization. Each coordination constraint represented by (21) corresponding to each scenario (F or M) can be represented as follows,

$$t_j^k - t_i^k \geq CTI \quad \forall \ (i,j) \ , and \ k \in K \quad (25)$$

where, K is the set of all coordination scenarios, (M, F) $\in K$. The objective function (20) can be re-formulated as,

$$min \ T = \sum_{r=1}^{R} C' x_r \quad \forall \ r \in R \quad (26)$$

where,

$$C' = \sum_{m=1}^{M} \sum_{f=1}^{F} c_{mf} \quad \forall \ m \in M, \ f \in F \quad (27)$$

subjected to,

$$A^k X \leq b^k, \ X \geq 0, \ k \in K \quad (28)$$

where, A^k represent the coordination constraint matrix consisting of the weighting coefficients c_{mf} in k^{th} scenario. C' is the coefficient vector of the objective function. Now, (26) and (28) are same as (6) and (7) and the optimization problem can be solved by using (10) to (12).

V. SIMULATION CASE STUDY

The relay coordination problem is evaluated using the proposed hybrid MPSO-ILP method on modified distribution section (highlighted in red color) of IEEE 14 bus standard benchmark system [18] shown in Fig. 2. The network is equipped with 5MVA, 10% reactance, synchronous type DGs connected to each bus in the distribution section. Isolated mode of operation is achieved by disconnecting the transformers connected between buses 6, 5 and 7, 4 respectively. Overcurrent relays with IEC standard inverse characteristics are considered for coordination. In this approach, the parameter limits considered for interval optimization are shown in Table I and the MPSO parameters are given in Table II. Load flow studies and fault studies are conducted on the system for near end, mid-line, far end and 10% distance each on the line. The system is tested under two configurations:

1) Grid Configuration : In this configuration the system is tested with all combinations of PS values with all fault scenarios and corresponding coordination constraints.

2) Isolated Configuration : In this configuration the system is tested with all combination of PS values with all the fault scenarios those tested for grid configuration, with coordination constraints of both grid configuration and isolated configuration.

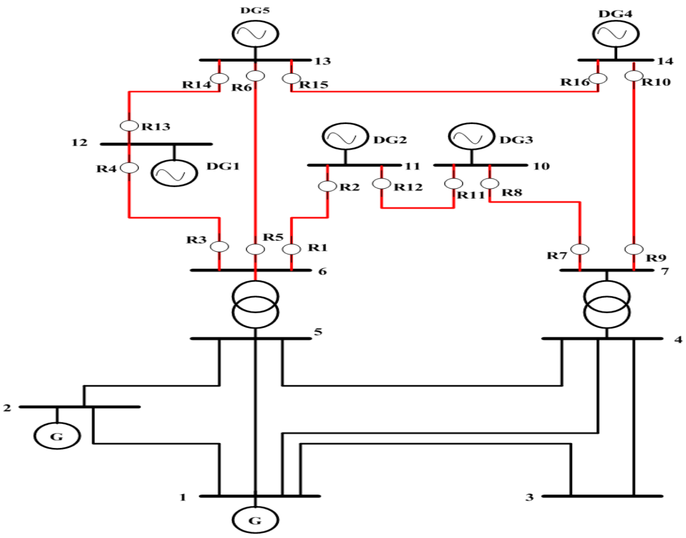

Fig. 2. Modified distribution system portion of IEEE 14 bus system

TABLE I
PARAMETER LIMITS CONSIDERED FOR INTERVAL OPTIMIZATION

TMS^{min}	0.1
TMS^{max}	1
PS^{min}	1.5*I_{load}^{max}
PS^{max}	(2/3)*I_{fault}^{min}
CTI^{min}	0.2 sec
CTI^{max}	0.5 sec
t^{min}	0.1 sec
t^{max}	1 sec

TABLE II
MPSO PARAMETERS

Initial velocity	0.1
Swarm count, n	100
w_{min} & w_{max}	0.9 & 0.4
c_1 & c_2	0.4 & 0.2

TABLE III
OPTIMAL RELAY SETTINGS AND OPERATING TIMES USING HYBRID MPSO - ILP APPROACH IN GRID CONFIGURATION

Relayno.	PS	TMS(sec)	t_{min}(sec)	t_{max}(sec)
R1	0.8433	0.2709	0.2116	0.5532
R2	0.8397	0.1187	0.2238	0.4798
R3	0.8390	0.1206	0.1246	0.6221
R4	1.4840	0.1162	0.1252	0.5116
R5	0.8396	0.1000	0.1373	0.7669
R6	0.8295	0.1000	0.2737	1.5965
R7	0.6887	0.2285	0.2296	0.5128
R8	0.8501	0.2081	0.3418	0.6233
R9	0.7708	0.2034	0.2728	0.4235
R10	0.8238	0.2573	0.3203	0.6718
R11	0.8918	0.2324	0.1735	0.5383
R12	0.8724	0.1982	0.2477	0.7103
R13	0.7893	0.1280	0.1483	0.6652
R14	0.6950	0.2096	0.2285	0.5277
R15	0.6468	0.1000	0.2763	0.7036
R16	0.9385	0.1000	0.2498	0.8532

TABLE IV
OPTIMAL RELAY SETTINGS AND OPERATING TIMES USING HYBRID MPSO - ILP APPROACH IN ISOLATED CONFIGURATION

Relayno.	PS	TMS(sec)	t_{min}(sec)	t_{max}(sec)
R1	0.6896	0.8034	0.2178	0.7886
R2	1.2955	0.4662	0.3589	0.8155
R3	0.6671	0.3204	0.4213	0.2152
R4	1.2923	0.5305	0.5624	0.3231
R5	0.6667	0.7946	0.5115	1.5153
R6	0.6667	0.9993	0.2147	1.3504
R7	0.6667	0.5404	0.3332	0.8477
R8	1.6407	0.3511	0.3601	0.8587
R9	1.1625	0.9804	0.2171	0.7498
R10	0.6742	0.4899	0.5698	1.3466
R11	1.3284	0.6982	0.1898	0.6170
R12	1.4889	0.5087	0.4531	1.1298
R13	0.8302	0.9978	0.3660	0.7508
R14	0.9545	0.5428	0.3152	0.8189
R15	0.6667	0.3487	0.2118	1.0950
R16	0.6667	0.9160	0.3255	0.8296

VI. RESULTS AND ANALYSIS

The proposed method is evaluated on the test system explained in section V using grid and isolated configurations. The optimal settings for both configurations obtained using proposed approach are shown in Table III and IV. The third and fourth columns of Table III and IV represent the operating times of relays when operating as primary relay and backup relay respectively. All parameters are within limits and no violations are observed in both configurations. For grid configuration, when standard MPSO is used for solving the problem, the optimal value is obtained after about 100 generations, whereas, the proposed method converged to the solution within 10 iterations. Fig. 3 shows the convergence graph of standard MPSO for ten random initial solutions versus the proposed hybrid MPSO - ILP approach, in grid configuration. Similarly, for isolated configuration, the standard MPSO is not able to converge to the optimal solution even after running for more than 1000 generations. In the case of proposed method, the optimal solution is obtained within 15 generations. Fig. 4 shows the convergence graph of standard MPSO for ten random initial solutions versus the proposed hybrid MPSO - ILP approach, in isolated configuration. These two figures show the strength of proposed method in converging to the optimal solution rapidly. It is to be noted that the relay operating times in isolated configuration are higher than those of grid configuration because of less short circuit MVA in isolated configuration. The fault current magnitudes seen by most of the relays in isolated configuration are less as compared with those in grid configuration. The coordination constraints corresponding to all fault scenarios are satisfied and are found to be within limits. Overall relay operating times are also less in grid configuration as compared to those of isolated configuration. Fig. 5 and Fig. 6 show the operating time vs fault location chart of relays R2 and R8 for fault on line 6-11. In this case R2 operates as primary relay and R8 as backup relay. From Fig. 5 and Fig. 6 it is clear that proper coordination is maintained between R2 and R8 for all fault locations in

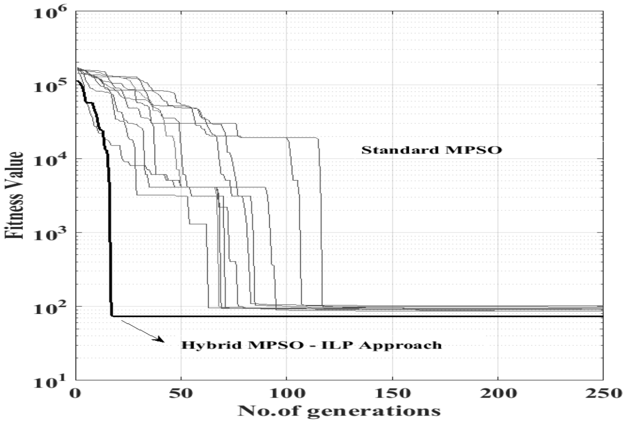

Fig. 3. Convergence of proposed Hybrid MPSO - ILP Approach vs Standard MPSO - Grid Configuration

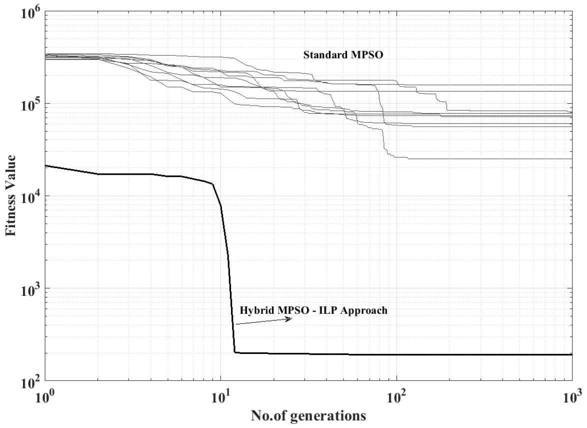

Fig. 4. Convergence of proposed Hybrid MPSO - ILP Approach and Standard MPSO - Isolated Configuration

both configurations in clearing the fault. Also, the primary relay operating times are well below limits. This example is worth enough to show the efficiency of proposed method in converging the problem to an optimal solution quickly in terms of number of generations as compared to the standard MPSO.

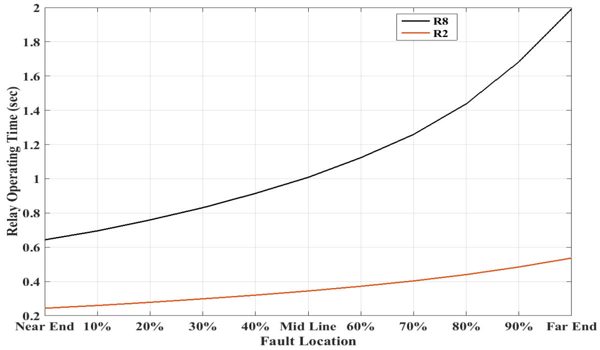

Fig. 5. Operating time vs Fault location chart of primary relay R2 and backup relay R8 for a fault on line 6-11 of test system in Grid Configuration

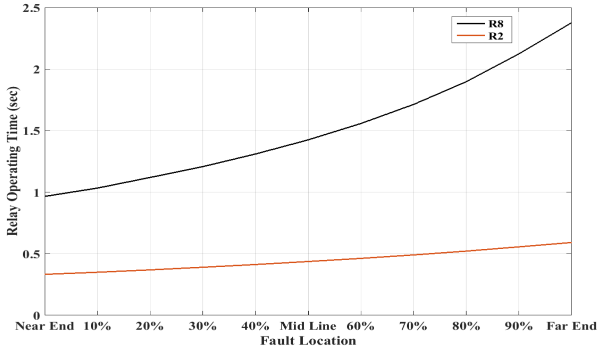

Fig. 6. Operating time vs Fault location chart of primary relay R2 and backup relay R8 for a fault on line 6-11 of test system in Isolated Configuration

VII. CONCLUSION

A solution to relay coordination problem in microgrid scenario by using hybrid MPSO - ILP approach is presented in this paper. ILP approach is used to handle the redundant constraints of the optimization problem when many fault scenarios are considered. The complexity of microgrid relay coordination due to bidirectional power flow, varied fault scenarios and configurations is successfully overcome by representing the fault current magnitudes as intervals and formulating a linear objective function.The constraint coefficients can also be represented as intervals and by optimally choosing Plug Setting (PS) values, the nonlinear objective function can be reduced to a linear objective function with interval coefficients. MPSO is applied to optimally choose the PS values and ILP problem is solved to obtain optimal TMS values. For the test system considered, the optimal solution is obtained for both grid and isolated configurations and it is shown that the proposed method convey good convergence characteristic as compared to standard MPSO. This work can be extended by including other scenarios like network topological changes like line outages, addition or disconnection of DGs etc.

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