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Optimal Coordination of Directional Overcurrent Relays for Microgrids Using Hybrid Interval Linear Programming - Differential Evolution

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Abstract- *The relay coordination problem of directional overcurrent has been an active research issue in distribution networks and power transmission. In general, the problem of relay coordination is the nonlinearity of the optimization problem, which increases or decreases with different network structures. This paper presents a new method with directional overcurrent relay coordination approach to reduce the operating time of the relays between the primary and backup relays by using hybrid programming of ILP (interval linear programming) and DE (differential evolution). Due to the difference in short circuit current level from grid connected to the isolated mode, therefore, it is necessary to use a reliable protection solution to reduce this discrimination time and also to prevent the increase of coordination time interval (CTI). The ability of the objective function used in this paper is to reduce the discrimination time of primary and backup relays and simultaneously reduce the operating time of primary and backup relays by introducing a new method. The basic parameters of the directional overcurrent relay (DOCR) such as time multiplier setting (TMS) and plug setting (PS) have been adjusted such that the relays operation time should be optimized. Optimization is based on a new objective function, described as a highly constrained non-linear problem to simultaneously minimize operating time in backup and primary relays. A function of penalty is also used to check the problem constraints in case the backup relay time is fewer than that of the main relay. The method is implemented on modified IEEE 14- and 30-bus distribution networks. The results demonstrate the efficiency of the method, and the values are optimal compared to those of other algorithms. MATLAB program has also been used to simulate optimization.*

Keyword: Microgrid; Relay Coordination; Directional Overcurrent Relay; Multi-Objective Optimization; Interval Linear Programming; Differential Evolution

1. INTRODUCTION

The ability to incorporate renewable electricity generation in the distribution system is one of the important reasons for the use of microgrid. A wide range of distributed generation (DG) technologies, such as micro-turbine generation, including wind generation, photovoltaic and energy storage systems, create the microgrid [1]. Due to the impact of microgrids on the performance of power grid protection systems, electrical service companies invest technical and economic resources to provide a reliable and reliable source of electricity based on appropriate components, reliable equipment, system structures and modern devices [2]. Directional relays are preferred to protect the distribution and transmission systems of power generation networks. Adjusting the optimal time settings of these relays according to different operating conditions, plays an important role in isolating to the fault point position of the power system [3]. Directional overcurrent should be coordinated to increase the reliability of the distribution system and minimize network outages in the event of abnormalities and faults. This coordination should be as optimal as possible to impose minimum damage and stress on the faulty equipment. Therefore, overcurrent relays coordination is an essential need in the operation and design of the distribution network. The main reasons for using microgrids are environmental conditions, concerns for climate change, and warnings issued by all experts about greenhouse gas emission [4]. Due to public consumption, there is a need for the local network, a need that is now being satisfied via the use of microgrids. A microgrid is a set of local loads and products that are often connected to the distribution

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network and are based on components such as power electronic devices, distributed products (wind turbines, solar panels, etc.), and storage devices that can be exploited in both grid connected and isolated from the network [5]. A microgrid has capabilities for operating grid connected and island modes and managing transitions between these two operation modes. In network connection mode, the main network can provide the deficiency of microgrid power, and the extra electricity produced in the microgrid can be exchanged with the main network [6]. However, the main problem of these networks is their protection, since the variety of these networks and the changes to their structure in connected and isolated modes of the primary network can alter the settings of their protective relay [7]. Most relays used in protective problems are mainly of the current types. The main problem with utilizing these relays is their current and time settings, whereas the level of the short circuit can be changed in different operating conditions. In different papers, ring networks are used to investigate the challenges of the protective relay setting [8]. As a result, using these types of conventional networks creates serious problems for relay settings because the consumers are not fed in one direction. This, in turn, causes the non-coordination of the relay settings compared to the one-directional state of feeding [9]. Various studies have been conducted on the current-time setting of directional overcurrent relays (DOCRs). In references [10-13], the relays have been set by linear programming; despite its simplicity and speed, it is relatively complex and does not have enough efficiency due to the non-linear nature of the relay setting. In references [14, 15], to optimize the coordination of relays, a DE algorithm has been adopted for solving the non-linear DOCRs coordination problem. In Ref. [16], mixed-integer linear programming (MILP) was employed for optimization, and the TMS and PS of relays were considered as the optimization variables. In references [17-19], intelligent methods such as GA (genetic algorithm) for the overall optimal solution and PSO (particle swarm optimization) are initialized with a population of random solutions. Each random solution has been assigned in PSO at a random speed according to the flight experience of oneself and one's neighbors; the random solution is called particles. Compared to GA, PSO has attractive features. It has memory and information is correctly stored in all the particles. In references [20-23], the firefly algorithm has been utilized to achieve overcurrent relay optimal coordination in power network protection while DG has been present in the system. Typically, the firefly algorithm works by selecting the parameters of the TMS and PS. The GRAVITATIONAL algorithm (GRA) is based on the gravity law. The agents in GRA are considered as objects with masses. Agents attract one another by the force of gravity. The higher the quality, the stronger the gravity. The advantage of ACO (ant colony optimization) compared with GA is the global memory role, played by the pheromone matrix, which leads to a faster and better solution. In Ref. [24] the overcurrent relay is used to adjust the dual setting direction using the time protection scheme and the current voltage characteristic (UDDOR-TCV) for radial distribution system. The proposed model is designed by constrained nonlinear optimization method which deals with nonlinear programming of complex integers.

The disadvantages of former optimization techniques and also metaheuristic optimizations, are prospects for integrating standards that may not be optimal in all cases, but are, instead, limited to a value of local optimal. Convergence has been used to solve the coordination problem of relays time. Occupying a large amount of memory and their disability to be applied in a variety of applications are some problems associated with these types of optimization methods. To solve these problems, linear and nonlinear hybrid optimization methods are used, and some of them are introduced: The hybrid improved harmony search algorithm (IHSA) with nonlinear programming (NLP) overcomes the advantages of both IHSA and NLP methods, and simultaneously, overcomes the disadvantages of these methods. In the hybrid modified PSO (MPSO)-ILP method in which pickup current settings are optimally found by PSO and time settings are calculated using ILP approach subjected to limit and coordination constraints. Hybrid GA-ILP where the PS is optimally found by GA and therefore the TMS are calculated using the ILP method subjected to limit and coordination constraints. The hybrid PSO-Dragonfly algorithm (DA) is applied in some unconstrained test functions without limitation and DOCR coordination optimization problems against test results in complex/constrained design [25-28]. In Ref. [29] a hybrid water cycle and moth flame (WMF) algorithm is used to solve the problem of optimal relay coordination in the microgrid. The suitability of the latest WCMF hybrid algorithm in a microgrid for TMS optimization is examined. An optimal TMS reduces the operating time of all relays installed in the microgrid. The Harris optimization hybrid algorithm uses sequential quadratic programming (HHO-SQP) to optimally coordinate overcurrent relays to find the optimal relay settings. The optimization problem based on an objective function developed is described as a nonlinear and highly constrained optimization problem to minimize the total operating time of the primary relays while maximizing the operating time of the backup relays [30].

DOCRs are extensively used to protect distribution networks and sub-transmission. The overcurrent relays act based on the current levels and have two main adjustable parameters: TMS and PS [31]. The magnitude and direction of the fault current are not constant in the relays because of the network structural changes caused by expected or unexpected occurrences. To overcome this problem, relay coordination can be solved by ILP. Accordingly, in Ref. [32], interval mathematics was used for modeling the uncertainties caused by the single exit of transmission lines in the problem of overcurrent relay coordination and choosing a setting for these relays.

Given the nonlinear nature of the coordination and adjusting the values of current-time setting in the DORs, in this paper presents a new method with directional overcurrent relay coordination approach to reduce the operating time of the relays between the primary and backup relays, to optimize multi-objective functions for obtaining PS and TMS DORs, the hybrid DE - ILP method has been used to coordinate the main relays and backup relays operating time separately in both grid connected and isolated modes of the network. The DE algorithm is used to calculate the PS current, and the ILP method is adopted to calculate the TMS of the relays. The location of the distributed generators (DGs) is considered as fixed with multiple faults' current scenarios (far-end and near-end each on the line). Because of the ring network, each fault is protected by two primary relays (one relay on each side). Therefore, in Sections 2 and 3, the ILP and DE algorithms are explained, respectively. In Section 4, the coordination structure of directional relays is examined. In Section 5, the hydride of the second and third sections and its use in coordinating directional relays are explained, and in Section 6, the efficiency of this method in a sample network is analyzed.

In this paper, assumptions will be considered which are:

- Only the steady state fault is considered. In addition, the transient states created by disconnecting and reconnecting the distributed generation sources are ignored.
- The designed protection system only responds to fault in microgrid lines and buses, and the fault in distributed generation sources is eliminated by the protection system itself.
- The location of the fault is known, so this article does not identify the location of the fault.

2. INTERVAL LINEAR PROGRAMING

In cases where the objective function or constraints are uncertain and the problem parameters are arranged as intervals, the ILP is used. The linear programming problem is expressed in Equation (1) [33].

$$\begin{aligned} &\min \ z = C^{IT} X = \sum_{j=1}^{q} \left[\underline{c}_j \ \overline{c}_j \right] x_j \\ &s.t. \quad \sum_{j=1}^{q} \left[\underline{a}_{ij} \ \overline{a}_{ij} \right] x_j \le \left[\underline{b}_i \ \overline{b}_i \right] \quad i = 1, 2, ..., p \\ &x_j \ge 0 \qquad j = 1, 2, ..., q \end{aligned} \tag{1}$$

where $\underline{cj}$ and $\overline{cj}$ show the minimum and maximum of coefficient xj in the objective function, respectively; $\underline{a_{ij}}$ and $\overline{a_{ij}}$ are the minimum and maximum coefficient values x_j in the ith constraint, respectively; $\underline{b_i}$ and $\overline{b_j}$ are the minimum and maximum values of b_j in this constraint, respectively. If for any (j), the relation $x_j \ge 0$ exists, then for the inequality of the interval $\sum_{j=1}^{q} \left[\underline{a}_{ij} \ \overline{a}_{ij} \right] x_j \le \left[\underline{b}_i \ \overline{b}_i \right]$, the possible largest and smallest regions are given in Equations (2) and (3), respectively.

$$\sum_{j=1}^{q} \underline{a}_{ij} x_j \le \overline{b}_i \quad i = 1, 2, ..., p \tag{2}$$

$$\sum_{j=1}^{q} \overline{a}_{ij} x_j \le \underline{b}_i \quad i = 1, 2, ..., p \tag{3}$$

The robust results of ILP presented in Equation (2) are obtained by solving the linear programming problem defined in Equation (4).

$$\begin{aligned} &\min \quad \sum_{j=1}^{q} \underline{c}_j x_j \ \ or \ \ \sum_{j=1}^{q} \overline{c}_j x_j \\ &s.t. \quad \sum_{j=1}^{q} \overline{a}_{ij} x_{1j} - \sum_{j=1}^{q} \underline{a}_{ij} x_{2j} \le \underline{b}_i \\ &i = 1, 2, ..., p, x_{1j} \ge 0, \quad x_{2j} \ge 0 \quad j = 1, 2, ..., q \end{aligned} \tag{4}$$

Using Equation (4), the number of optimization constraints in all network structures is equal to the number of constraints in the main network structure. This is because of using Equation (4) instead of examining coordination constraints in all network structures, whereby only the worst constraint among all the constraints is considered.

3. DIFFERENTIAL EVALUATION

The DE was introduced by Price and Stone. They proved that this algorithm is potent in optimizing nonlinear functions, so it was described as an efficient method for solving the nonlinear functions' optimization problem. The DE algorithm has been presented to correct the main fault of the genetic algorithm, namely, as lack of local searching. The main difference between the GA and DE algorithms is selecting the operator. In this algorithm, unlike others, first, the crossover operator is selected, and then mutation occurs [34]. The main steps of the DE are shown in Fig. 1.

In an optimization problem, we need to minimize f(x) according to Equation (5):

$$\text{Min } f(x),\ x=[x1, x2, \ldots, xd] \qquad (5)$$
$$\text{S.t } xi \in [ai, bi]$$

Where function f (x) is the objective function, the decision vector x consists of variable d, and a_i and bi represent the lower and upper bounds of xi, respectively. The steps of DE are as follows:

3.1. Initial Value

The individuals in DE are as follows in Equation (6):

$$X_{ig} = [x_{i1g}, x_{i2g}, \ldots, x_{iDg}] \qquad (6)$$
$$i \in \{1,2, \ldots, NP\}$$

Where x_{ij}^{g} represents the candidate parameter for the j_{th} individual of the g_{th} generation in function f (x), NP is the population size, and D is the objective function.

3.2. Mutation

For each vector x_{ig}, DE plots a mutation vector v_{ig} based on the difference between vectors randomly selected from the population. According to Equation (7):

$$V_i^g = X_{r3}^g + F^k \cdot (X_{r2}^{gk} - X_{r1}^{gk})$$
$$r_1, r_2, r_3 \in \{1, 2, ..., N\} \qquad (7)$$
$$F^k \in [0,1] \qquad k \in [1, 2]$$

Where F^k is the mutation factor related to convergence, which is usually between 0 and 2. X_{r1}^g ، are the individuals who are randomly X_{r3}^g and X_{r2}^g selected from the population and are different from those X_i^g who are moving.

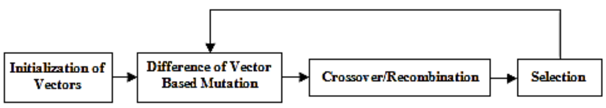

Fig.1. Main steps of the DE algorithm

3.3. Crossover

In the crossover, the child vector is presented in Equation (8):

$$U = \begin{cases} V & rand(j) \le CR \\ X & rand(j) > CR \quad j \in \{1, 2, ..., D\} \end{cases} \qquad (8)$$

Where V_{ig}^g is a parameter in the vector of the candidate child U_i^g , and V_{ig}^g is a parameter in vector V_i^j . CR is the crossover rate which is limited to [0, 1].

3.4. Selection

Selection acts as a competitive mechanism. According to Equation (9):

$$X_i^{g+1} = \begin{cases} U_i^g & if \quad f(X_i^g) > f(U_i^g) \\ X_i^g & otherwise \end{cases} \qquad (9)$$

DE will repeat the process of crossover and selection, until the ending conditions are met, and its output is a solution for $f(x)$.

4. COORDINATING STRUCTURE OF DIRECTIONAL RELAYS

Obtaining PS and TMS for every relay is the main purpose of coordinating DOCRs; therefore, it is necessary to minimize the objective function (OF) to coordinate the relays. The objective function is usually represented by Equation (10):

$$\min OF = \sum_{i=1}^{m} w_i . t_i \qquad (10)$$

Where t_i the operating time of ith relay i for the fault in line l, w_i is the weight considered for the operating time R_i , and m is equivalent to network relay numbers. Equation (10) has two basic problems. One is the lack of effectiveness in adding the relay coordination time (CTI) in large networks, and the other is a lack of relay coordination. To overcome these two problems, Equation (11) is considered as OF to coordinate the relays [35]:

$$OF = \alpha_1 \sum_{i=1}^{m} t_i^2 + \alpha_2 \sum_{k=1}^{n} (\Delta t_{mbk} - \beta_2 (\Delta t_{mbk} - |\Delta t_{mbk}|))^2$$
$$\Delta t_{mbk} = t_{bk} - t_{mk} - CTI \qquad (11)$$

In Equation (11), t_{mk} and t_{bk} are equal to the operating time of the primary and the backup relay, respectively; m and n are equal to the number of main and backup relays, respectively; and k refers to each of the primary and backup relays. Moreover, α_1 and α_2

of the OF are used to control the weight, and β_2 is used for lack of coordination. Based on Equation (11), if Δt is negative, for positive values β_2, the value of the OF function is greater than the state in which Δt is negative. In Equation (12) [35], the objective function is defined as:

$$OF = \alpha_1 \sum_{i=1}^{m} t_i^2 + \alpha_2 \sum_{k=1}^{n} (\left|\Delta t_{mbk} - |\Delta t_{mbk}|\right|.t_{mk}^2 + (\Delta t_{mbk} + |\Delta t_{mbk}|).t_{bk}^2) \quad (12)$$

Assume that Δt_{mbk} is positive; thus, the third part of Equation (12) has value, and this value is due to coefficient t_{bk}^2. Therefore, Equation (12) tries to reduce further the optimal time to prevent the adverse increase in the optimal time of the main relay. Given that, in most intelligent relays, the PS is considered constant and the optimal amount of operating time is considered as a linear function of TMS, there is a need for a method that uses TMS and PS simultaneously. In most available methods, the relay coordination problem is solved based on a critical point (fault at the beginning or end of the line). Therefore, it is necessary to employ a method that considers the fault at the end and beginning of the line. Fig. 2 displays the fault location at the end and near on the line. DOCRs coordination problem formulation to minimize the operating time of the primary relays in accordance with the limitations of the relay setting and the faults occurring in the network are the main goals of solving the coordination problem of DOCR. In the coordination problem of DORs, the objective function is minimizing total relays operating time existing in the network. The optimization function should generally be considered as Equation (13):

$$OF = \min \sum_{i=1}^{Nr} t_i \quad (13)$$

For each main relay i and backup j, Equation (14) is presented:

$$\left(t_j - t_i\right) \geq CTI \quad (14)$$

In Equation (13), Nr is the number of relays and ti is the operating time of the ith relay. When processing the optimization steps, the constraint considered in Equation (14) may be violated. In this case, based on Equation (15), a penalty function is taken into account in this paper to consider the penalty of the violated cases.

$$\boldsymbol{OF_{penalized}} = OF + PF \quad (15)$$

$OF_{penalized}$ is the value of the function considering the penalty; OF is the objective function specified in Equation (13) without considering the penalty; and PF is the function of the penalty. The value of PF is determined by Equation (16) [36]:

$$PF = \sum_{i=1}^{Nr} Viol(i) \quad (16)$$

To determine the Viol values, first, according to Equation (17):

$$viol\left[1:NR\right] = 0 \quad (17)$$

In this case, if Equation (16) is not correct, we will use Equation (18):

$$viol(i) = viol(i) + cons\tan t \quad (18)$$

The expression constant is a fixed positive numerical value intended for a penalty. Considering the penalty value, the values that violate Equation (14) are discarded. Then, considering the fault at the near and end of the line, Equations (19) and (20) are used to optimize the relays operating time and consider the conditions of Equation (15); both equations specify the minimum main relays and the backup relays operating time, respectively [37]:

$$OF_1 = \min \sum_{i=1}^{Np} t_i \quad (19)$$

$$OF_2 = \min \sum_{j=1}^{Nb} t_j \quad (20)$$

In Equations (19) and (20), ti and tj denote the main and backup relays operating time, respectively, and Np and Nb represent the number of primary and backup relays, respectively.

5. PROPOSED METHOD

The main objective of this paper (21) is to optimize the operating time of DOCRs when they are considered as the main and backup relay simultaneously. This optimizes not only the operation time of main relays, but also the operation time of backup relays. Subsequently, we use Equation (21) for the objective function, which is obtained by combining Equations (19) and (20). According to Equation (16), the penalty function is used to check the correct coordination of the operating time of the main and backup relays:

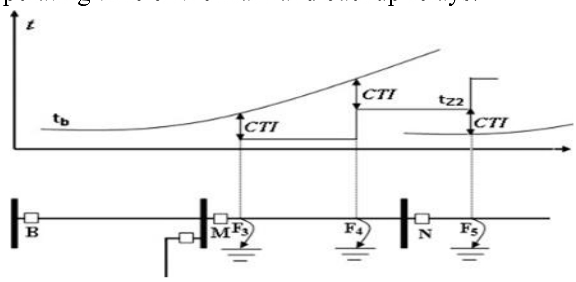

Fig.2. The location of the fault at the end and near of the line

Table 1. Coefficients used in Equation (23)

Number of characteristic (Rc)	Type of characteristic	α	β	standard
1	Standard Inverse	0.14	0.02	*IEC*
2	Very Inverse	13.5	1	*IEC*
3	Extremely Inverse	80	2	*IEC*

$$OF = \min(\sum_{i=1}^{N_p} t_{\min}(i) + \sum_{i=1}^{N_b} t_{\max}(i)) \tag{21}$$

$t_{\min}$ and $t_{\max}$ are the operating times of the relays, which operate as the primary relay and the backup relay, respectively. Because the fault values are considered at the beginning and end of each line, the following values should be checked according to Equation (22):

$$\begin{aligned} t_b(f_i) - t_p(f_i) \geq CTI \\ t_b(f_j) - t_p(f_j) \geq CTI \end{aligned} \tag{22}$$

The values of tp (fi) and tb (fi) are the operating time of the main and backup relays at the near and end of the bus, respectively. CTI is a constant value considered to coordinate the time of operation between the main and backup relays, and its value is between 0.2 and 0.5. As shown in Equations 11 and 12, the presence of Δt in the objective function can lead to an increase in the optimal time. According to Equation 21, due to the removal of the value of Δt in the objective function, the coordination problem of DOCR relays can be easily solved using the ILP-DE method. Instead, in order to reduce the discrimination time of the primary and backup relays, a separate objective function is considered to determine the optimal time of the backup relays, such as the optimal time of the primary relays. Therefore, increasing the optimal time of the primary relays does not lead to obtaining incorrect values of the objective function. In addition, using the objective function used in this paper, there is no need to use weighting factors such as Equation 10. In addition, in each step, a penalty value in accordance with Equation 15 is used to check that the backup relay time is larger than the main relay. Finally, the output results contain the settings by which the discrimination time of primary and backup relays are minimized without the mentioned problems. For each protection relay, the operating time t is obtained from Equation (23):

$$t_{ij} = \frac{\alpha \times TMS_{ij}}{(\frac{If_{ij}}{Ip_i})^{\beta} - 1} \tag{23}$$

Where t is the operating time of the relay, I_f is the fault current passing through the relay and short circuit calculations in the network have been used to obtain the fault current. Due to the fact that the three phase short circuit current intensity is in most cases greater than all asymmetric fault currents. So it is enough to calculate this current and adjust the current of the relays setting based on this current. Ip is equal to the setting current on the relay after which the relay starts operating and where *i* is the relay identifier, *j* is the fault location identifier. TMS_{ij} and Ip_i are the TMS and Ip of i[th] relay for an j[th] fault location. The values for Equation (23) are listed in Table 1. The constraints used to coordinate the relays also need to be optimized. These constraints are:

5.2. Values of TMS

This value sets the operating time of the relays before they operate and when the fault current is equal to or greater than the set value, and is determined by Equation (24):

$$TMS_{min} \leq TMS \leq TMS_{max} \tag{24}$$

5.3. Primary Relay Operation Time

Equation (25) is used to ensure that the main relays operating time of is set correctly and the fault is stopped at the correct time:

$$t_p^{\min} \leq t_p \leq t_p^{\max} \tag{23}$$

5.4. Values of PS

Ip is the current after which the current to the relay operates according to the time-current curve, and its value must be limited by Equation (27):

$$Ip^{\min} \leq Ip \leq Ip^{\max} \tag{24}$$

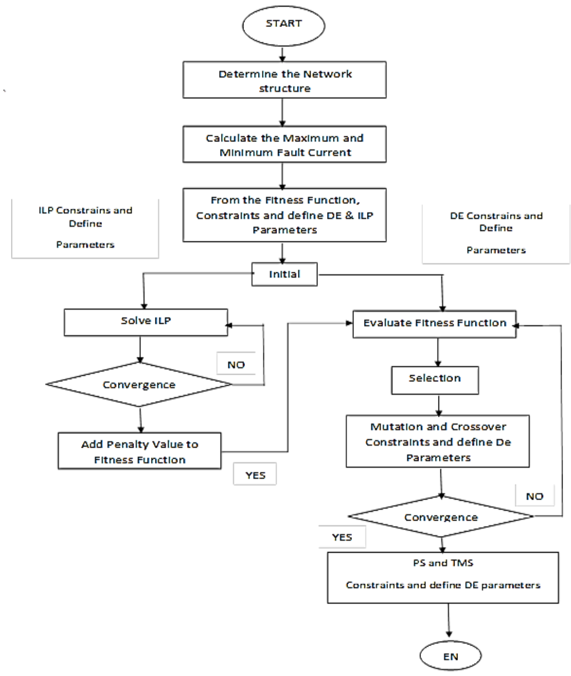

Fig.3. Flowchart for the implementation of hybrid DE-ILP to coordination of relay

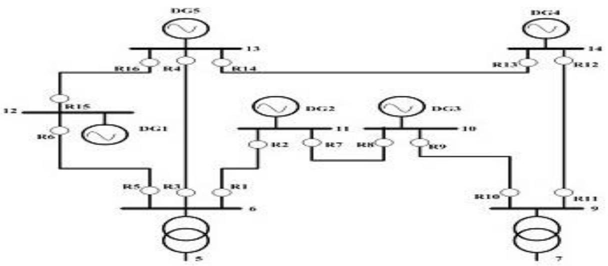

Fig.4. Modify IEEE 14-bus network

In Equation (27), $Ip^{\min}$ and $Ip^{\max}$ are the minimum and maximum values of the relay setting current, in that order. Therefore, the PS value is limited according to Equation (28):

$$PS^{\min} \le PS \le PS^{\max} \qquad (25)$$

To ensure that the relay does not operate in normal operation, the minimum value considered for the PS is such that the relay does not operate up to 1.25 load current [38].

First, a random initial value is generated. The initial and random values of PS are then determined. Next, the value of the objective function's initial value in DE is defined using (10). In the problem of hybridizing ILP with DE, the ILP program is utilized as a sub-program for solving DE. The output of DE, PS, is given to the ILP program to find the optimal solution, and ILP calculates TMS. Fig. 3 illustrates the flowchart of the problem-solving method.

6. SIMULATION OF THE PROPOSED METHOD AND ANALYSIS OF THE RESULTS

To test the method used in this article, we have utilized two sample networks: modified IEEE 14- and 30-bus networks. The TMS value range of 0.1 to 1.1, and the PS range of 0.5 to 2.5 are taken into account. The CTI pair of relay P / B and the minimum operating time of 0.2 seconds is assumed in all cases.

Case A: Modify IEEE 14-bus network

To simulate the proposed method, an IEEE 14 bus network [39] is selected (Fig. 4). Using the proposed method, in all the relays, TMS, PS and their operating times are obtained at the optimal point. The microgrid is connected to the main network by two transformers placed between buses 6, 5 and 7, 4, respectively, through which they can be isolated from the main network and can operate as an island. To protect the microgrid, directional current relays are employed with a standard inverse time-current curve based on the IEEE standard. Furthermore, the microgrid is equipped with synchronous-type DGs, 5 MVA, 10% reactance, and connected per bus in the distribution section.

Table 2. Comparison of PS and TMS when connected to the main network

	ILP+MPSO		ILP+DE	
Relay no.	PS	TMS (sec)	PS	TMS(sec)
R-1	0.8433	0.2709	0.8310	0.2268
R-2	0.8397	0.1187	0.8279	0.1181
R-3	0.8390	0.1206	0.8274	0.1201
R-4	1.4840	0.1162	1.4780	0.1152
R-5	0.8396	0.1000	0.8396	0.1000
R-6	0.8295	0.1000	0.8238	0.1000
R-7	0.6887	0.2285	0.6610	0.2237
R-8	0.8501	0.2081	0.8441	0.1983
R-9	0.7708	0.2034	0.7128	0.1924
R-10	0.8238	0.2573	0.8107	0.2491
R-11	0.8918	0.2324	0.8826	0.2253
R-12	0.8724	0.1982	0.8601	0.1892
R-13	0.7893	0.1280	0.7655	0.1184
R-14	0.9650	0.2096	0.6793	0.1991
R-15	0.6468	0.1000	0.6394	0.1000
R-16	0.9385	0.1000	0.9308	0.1000

Table 3. Comparison of t_{min} and t_{max} when connected to the main network

	ILP+MPSO		ILP+DE	
Relay no.	t_{min} (sec)	t_{max} (sec)	t_{min} (sec)	t_{max} (sec)
R-1	0.2116	0.5532	0.1768	0.4610
R-2	0.2238	0.4798	0.2218	0.4734
R-3	0.2146	0.6221	0.1224	0.6131
R-4	0.1252	0.5116	0.1240	0.5028
R-5	0.1373	0.7669	0.1342	0.7649
R-6	0.2737	1.5965	0.2730	1.5716
R-7	0.2296	0.5128	0.2232	0.4951
R-8	0.3418	0.6233	0.3251	0.5921
R-9	0.2728	0.4235	0.2538	0.3909
R-10	0.3203	0.6718	0.3091	0.6463
R-11	0.1735	0.5383	0.1680	0.5199
R-12	0.2477	0.7103	0.2358	0.6730
R-13	0.1483	0.6652	0.1346	0.6013
R-14	0.2285	0.5277	0.2162	0.4970
R-15	0.2763	0.7036	0.2750	0.6954
R-16	0.2498	0.8532	0.2490	0.8486

Table 4. Compare of PS and TMS are isolated from main network

	ILP+MPSO		ILP+DE	
Relay no.	PS	TMS (sec)	PS	TMS(sec)
R-1	0.6896	0.8034	0.6808	0.7921
R-2	1.2955	0.4662	1.2161	0.4573
R-3	0.6671	0.3204	0.6612	0.3185
R-4	1.2923	0.5305	1.2796	0.5237
R-5	0.6667	0.7946	0.6585	0.7905
R-6	0.6667	0.9993	0.6588	0.9987
R-7	0.6667	0.5404	0.8588	0.5391
R-8	1.6407	0.3511	1.6393	0.3498
R-9	1.1625	0.9804	1.1385	0.9766
R-10	0.6742	0.4899	0.6997	0.4811
R-11	1.3284	0.6982	1.3196	0.6907
R-12	1.4889	0.5087	1.4812	0.5000
R-13	0.8302	0.9978	0.8289	0.9940
R-14	0.9545	0.5428	0.9499	0.5394
R-15	0.6667	0.3487	0.6589	0.3413
R-16	0.6667	0.9160	0.6559	0.9082

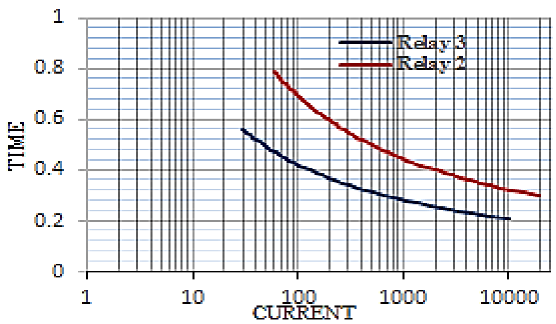

Fig.5. Time-current curve of relay R3 and its backup R2

According to Tables 2 and 3, the settings' values are optimized when the microgrid is connected to the network compared to the results of reference [28]. Tables 4 and 5 show the comparison of the proposed method with the method discussed in [28] in an isolated mode of the network. The comparison of these methods shows that the parameters evaluated in the proposed method are improved more than those adopted in the other method. In this method, the times are adjusted and the relay operating time is more optimized. Checking the relay operation time in network-connected and isolated mode indicates that the relay operation time in the connected mode is less than in the isolated mode, which is because of the high short-circuit MVA in the connected configuration.

The DE, PSO, ILP, GA, MPSO+ILP, and DE+ILP are run to solve the in-grid configuration, and the results obtained after optimization are given in Table 6. According to Table 6, the method used in this paper improves the operating time. Also, the DE, PSO, ILP, GA, MPSO+ILP, and DE+ILP are run to solve the isolated configuration, and the results obtained after optimization are given in Table 7. Fig. 5 shows the time-current curve of relay R3 and its backup R2. The curves are shown when the microgrid is isolated from the network. According to Fig. 5, the operation of the backup relay is after the main relay.

Table 5. Compare of t_{min} and t_{max} are isolated from main network

Relay no.	ILP+MPSO t_{min} (sec)	ILP+MPSO t_{max} (sec)	ILP+DE t_{min} (sec)	ILP+DE t_{max} (sec)
R-1	0.2178	0.7886	0.2146	0.7759
R-2	0.3589	0.8155	0.3492	0.7865
R-3	0.4213	0.2155	0.2137	0.4180
R-4	0.5624	0.3231	0.3186	0.5543
R-5	0.5115	1.5153	0.5082	1.5020
R-6	0.2147	1.3504	0.2144	0.3468
R-7	0.3332	0.8477	0.3320	0.8432
R-8	0.3601	0.8587	0.3587	0.8552
R-9	0.2171	0.7498	0.2160	0.7449
R-10	0.5698	1.3466	0.5635	1.3430
R-11	0.1898	0.6170	0.1877	0.6098
R-12	0.4531	1.1298	0.4450	1.1085
R-13	0.3660	0.7508	0.3655	0.7456
R-14	0.31152	0.8189	0.2978	0.8128
R-15	0.2118	1.0950	0.2070	1.0660
R-16	0.3255	0.8296	0.32245	0.8211

Table 6. Comparison of the results obtained from different methods in grid configuration

METHOD	DE	PSO	ILP	GA	MPSO+ILP	DE+ILP
$OF=\min(\sum_{i=1}^{Np} t_{\min}(i) + \sum_{i=1}^{Nb} t_{\max}(i))$	17.9	19.03	18.7	21.29	14.43	13.78

Table 7. Comparison of the results obtained from different methods in isolated configuration

METHOD	DE	PSO	ILP	GA	MPSO+ ILP	DE+ ILP
$OF=\min(\sum_{i=1}^{Np} t_{\min}(i) + \sum_{i=1}^{Nb} t_{\max}(i))$	21.8	23.8	23.07	24.3	19.68	18.44

Table 8. The values of t_{min}, TMS, PS, and t_{max}

Relay No.	PS	TMS	t_{min} (sec)	t_{max} (sec)
1	2.2	0.2	0.616	0.832
2	2.1	0.127	0.35	0.767
3	2.4	0.159	0.632	0.729
4	2.4	0.15	0.529	0.709
5	2.5	0.127	0.405	0.583
6	1.39	0.11	0.383	0.452
7	1.39	0.1	0.251	0.465`
8	1.11	0.1	0.232	0.343
9	2.4	0.236	0.664	0.764
10	2.4	0.225	0.623	0.867
11	2.3	0.179	0.667	0.739
12	2.4	0.174	0.564	0.742
13	2.5	0.136	0.54	0.658
14	2.5	0.125	0.542	0.835
15	2.225	0.1	0.458	0.738
16	0.987	0.293	0.636	0.805
17	1.135	0.117	0.244	0.348
18	2.5	0.148	0.509	0.764
19	2.3	0.168	0.542	0.731
20	2.28	0.123	0.43	0.864
21	1.284	0.142	0.33	0.864
22	2.5	0.171	0.569	0.63
23	2.4	0.163	0.627	0.879
24	2.5	0.122	0.624	0.839
25	2.5	0.169	0.678	0.824
26	0.5	0.1	0.305	0.305
27	0.5	0.1	0.265	0.357
28	1.23	0.2	0.74	0.883
29	2.12	0.1	0.469	0.864
30	2.4	0.126	0.594	0.669
31	2.5	0.16	0.667	0.94
32	2.4	0.149	0.645	0.793
33	2.4	0.2	0.634	0.867
34	2.5	0.188	0.605	0.843
35	2	0.168	0.542	0.836
36	0.5	0.15	0.298	0.39
37	2.3	0.142	0.533	0.828
38	2.4	0.133	0.565	0.806
$\sum_{i=1}^{np} t_{\min(i)}$ = 18.736 (s)			$\sum_{i=1}^{nb} t_{\max(i)}$ = 25.891 (s)	
OF= 44.627 (s)				

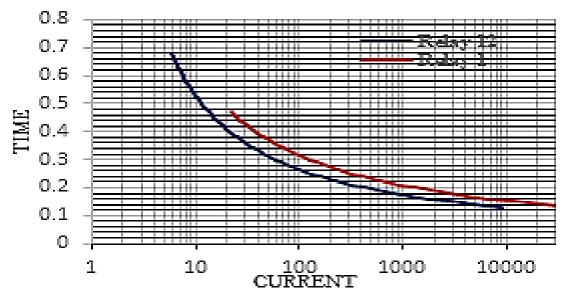

Fig.6. Time-current curve of relay R12 and its backup R1

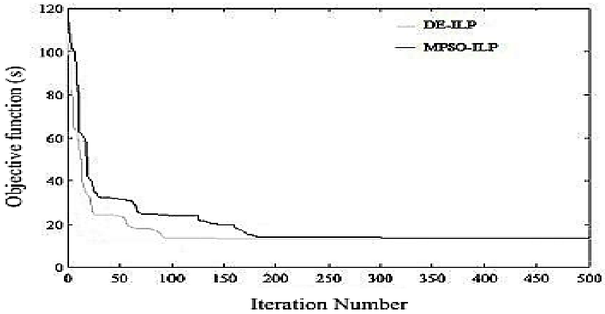

Fig.7. The Convergence of the recommended hybrid DE-ILP method and hybrid MPSO-ILP - grid configuration

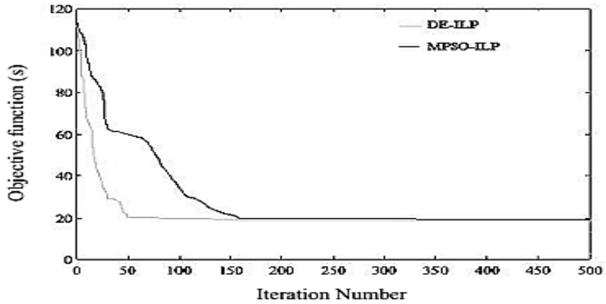

Fig.8. The Convergence of the recommended hybrid DE-ILP method and hybrid MPSO-ILP - isolated configuration

Fig. 6 depicts the time-current curve of relay R12 and its backup R1. The curves are shown when the microgrid is connected to the network. Based on Fig. 6, the operation of the backup relay is after the main relay. The proposed method is evaluated in the experimental system described in Section 6 using isolated and grid connections. The optimal settings for both configurations using the proposed method are presented in Tables 2-5. The columns of Tables 3 and 5 show the relays operating times, which operate as primary and backup relay, respectively. All the parameters are within the allowable range, and no violation is viewed in either configuration. For the configuration of grid connected, when the ordinary MPSO-ILP is used to solve the problem, the optimized value is gained after about 320 generations, while the suggested method converges into the solution in 80 iterations (Fig.7). As previously explained, the coordination algorithm is run for the isolated mode considering the coordination limits of both isolated and grid configurations. Therefore, the settings of relays in Table 5 show the optimal solution to the problem. For this configuration, the MPSO-ILP can converge to the optimal solution after 350 generations. In the case of the suggested method, the optimal solution is obtained in 140 generations (Fig.8). These two figures show the strength of the suggested method in converging rapidly to the optimal solution. Note that the relay operation time in the isolated configuration is higher than the grid configuration time due to the less short-circuit MVA in the isolated configuration. The magnitudes of the fault current observed by most of the relays in the isolated configuration are less than that in the grid configuration. The coordination limits related to the considered fault scenarios are satisfied, and it is clear that they are within the constraints. In general, the operating times of the relay are fewer in the configuration of grid connected in comparison to those of isolated configuration. Fig. 5 displays the performance time versus fault location diagram of relays R2 and R8 for the fault on lines 6-11. In this case, R2 acts as the primary relay and R8 as the backup relay. Fig. 6 illustrates the time-current curve of relay R12 and its backup R1. The curves are shown when the microgrid is connected to the network. Based on Fig.5 and 6, the proper coordination between R2-R8 and R1-R12 is maintained for all the faults of location in both configurations in fault clearance, and the operating times of the primary relays are way below the limits.

Case B: IEEE 30-bus network

To confirm the effectiveness of the recommended method, its performance must be evaluated in a larger system. The IEEE 30-bus system distribution network used for this purpose is presented in Fig.7. This distribution network is stable by three 50MVA, 132/33 kV power transformers connected to buses 13, 6, and 1. Despite the concentration of more than three sources, the two DGs connected to buses 15 and 10 also provide power in the same way. Distribution network data are presented in Ref. [41]. This distribution network has 20 lines (L1, L2, L3… L19, L20) and is protected by 39 DOCRs (R1, R2, R3… R38, R39) with 64 sets of essential amplifiers among them. The fault current that goes through main/backup DOCRs for near-end overcurrent faults is defined in [39-41]. The ratio of CT for each DOCR is 500:1. The lower and upper limits of PS and TMS are set to 1.5 and 2.5 for PS and 0.1 and 1.2 for TMS, respectively for CTI 0.3 seconds is assumed.

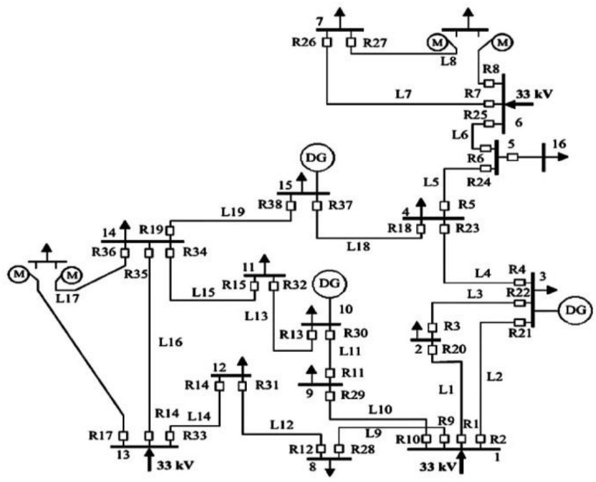

Fig.9. The IEEE 30-bus system distribution network

Table 8. Comparison of the suggested DE-ILP with the algorithms used in reference [42] for the IEEE 30-bus distribution network

METHOD	Objective Function
GA[42]	58.64 (s)
PSO[42]	69.31 (s)
DE[42]	49.28 (s)
DE-ILP	44.627 (s)

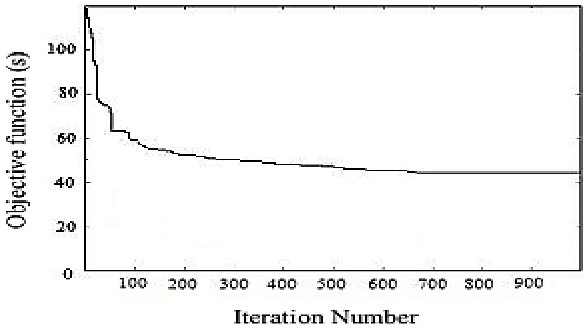

Fig.10. Convergence of the proposed hybrid DE-ILP approach in the IEEE 30-bus distribution network

In Table 7, the values of t_{min}, TMS, PS, and t_{max} by considering coordination constraints for both near-end and far-end faults are given. The optimal settings of TMs and PS for the IEEE 30-bus distribution network using the suggested method are shown in Table 8. Table 8 presents the operating times of the relays, which operate as a main and a backup relay, respectively. Table 9 gives the result of the suggested DE-ILP with other methods cited in the literature. According to Table 8, the objective function used in this paper has optimized the relays operating time compared to other methods. The convergence of the hybrid DE-ILP is obtained for the 30-bus network and showed in (Fig.10). A comparison of the suggested DE-ILP with the algorithms used in Ref. [42] for the IEEE 30-bus distribution network is demonstrated in Table 8.

The DE-ILP method was adopted to evaluate the problem of DOCRs coordination. The proposed method has convergence fast and convergence high search capability to other methods, and these specific features make DE-ILP search agents more different in finding the desired result compared to other methods. The case studies presented in this article have also been assessed by the various optimization methods introduced in the article, and an improved optimal solution of the suggested DE-ILP method compared to other methods has been observed. The problem of DOCRs coordination is constrained optimization problem. Since the DE-ILP can solve unconstrained and problems of constrained optimization, the problem of relay coordination has become a problem of unrestricted optimization by defining a new objective function and using the PS and TMS boundaries (and operation time of relay limits) as the variables' constraint. A systematic method to convert the problem of relay coordination into an optimization problem is developed in this article. The TMS, PS and relays operating time obtained for all case studies suggested by the DE-ILP ensure that DOCRs are activated in the shortest possible time for faults anywhere in the network. However, if the relays number increases, the importance of the highly constrained problem becomes more salient. Therefore, precise and optimal relay coordination minimizes the total operating time and also reduces the damage generated by the fault. This method prevents unnecessary power outages due to incorrect tripping of overcurrent relays. The convergence characteristic diagrams of the simulation indicate that the convergence is faster and obtains a better solution for the "*OF*" objective function in fewer iterations. In terms of solution quality, the proposed method tries to converge and minimize the objective function compared to the optimal value of the recently published methods mentioned in the article. In addition, the proposed method attempts to address the deficiencies of other optimization methods.

7. CONCLUSIONS

In this paper, the problem of DOCRs coordination optimization in the microgrid is presented by a characteristic function of nonlinear relay and a range of nonlinear coordination constraints. A detailed formulation of the problem of optimal DOCRs coordination in variable network stretchers is introduced. This study suggests a DE-ILP method to find an optimal solution for the problem of complex optimization such that a large number of coordination constraints corresponding to various network structures and many fault scenarios are simultaneously satisfied. The ILP method is employed when there is a problem with the constraints caused by different short-circuit current fault scenarios. The complexity of overcurrent relays optimal coordination in a microgrid due to bidirectional power flow, varied fault scenarios, and various network topologies are successfully overcome by presenting the fault current magnitudes as intervals and formulating a linear objective function. The ILP is solved to optimally choose the TMS values, and DE is applied to obtain the optimal PS values. Optimization is developed based on a new non-linear highly constrained objective function to simultaneously reduce operating time in backup and primary relays. This paper presents a new method with directional overcurrent relay coordination approach to reduce the operating time of the relays between the primary and backup relays by using hybrid programming of ILP (interval linear programming) and DE (differential evolution).

Therefore, it is necessary to use a reliable protection solution to reduce this discrimination time and also to prevent the increase of coordination time interval (CTI). The ability of the solution used in this paper is to reduce the discrimination time of primary and backup relays and simultaneously reduce the operating time of primary and backup relays by introducing a new method. Moreover, a penalty function is utilized to check the problem constraints in case the backup relay time is less than that of the main relay. The proposed algorithm is applied to modify IEEE 30 and 14-bus distribution networks, and all the results display the advantages of this objective function and algorithm.

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