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Optimal Protection Coordination for Microgrid Considering DG and Line Outages Using IWO-ILP Technique

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***Abstract*—Microgrids incorporated with synchronous distributed generators (SDGs) contribute to the significant amount of fault currents compared to inverter-based DGs. During islanded mode also, the fault magnitudes are significant and call for efficient and fast protection schemes. The coordination protection devices, especially, directional overcurrent relays (DOCRs) is a vital issue when dealing with microgrids with SDGs. In addition to the connection of DGs, frequent line outages affect the DOCR settings and cause device maloperation leading to miscoordination issues. This paper deals with optimal coordination of DOCRs for microgrids considering DG and line outages. A coordination model is proposed which involves the constraints corresponding to all N-1 contingencies, which can be a result of line / DG outage. In addition, cases of multiple fault locations are also included in the model to provide effective settings under all circumstances. The problem is modeled as a linear interval programming (ILP) problem and solved using invasive weed optimization (IWO) method. The ILP problem is stated as a sub-problem to IWO which would make it a hybrid optimizer. The proposed method is tested on 9 bus microgrid test system and results are presented.**

I. INTRODUCTION

Distributed generation (DG) integration into power system networks is showing a significant impact in reducing global carbon footprint by increasing eco-friendly power generation. Majority of developed and developing countries have already installed and successfully running renewable energy generating stations. When DGs are connected to the distributed network, the network gains the capability to temporarily or for a significant amount of time, operate as an islanded network. Such islandable distribution network or a portion of distribution network can be named as a microgrid. Microgrid operation leads to bi-directional power flow and makes radial lines to be non-radial [1]. Though such an operation has several advantages, it has many challenges to be faced like protection coordination issues, personnel safety etc. As synchronous DGs account for the significant magnitude of fault currents even in the islanded mode of microgrid operation, protection becomes an accountable challenge to be addressed.

Among many challenges faced by microgrid operation, one major challenge to be accounted for is the protection coordination issue [2]. Because, as the magnitude of fault currents vary with the islanded mode of operation, the operating times of protection devices like directional overcurrent relays (DOCRs) change and tend to miscoordinate, leading to device maloperation. In addition, by including line and DG outages into account, it would be tedious to recalibrate the DOCR settings for each network contingency viz., line outage, connection or disconnection of DG, change microgrid operation mode from grid connected (GC) to islanded (IS). Hence a comprehensive coordination model that would consider all operating constraints corresponding to N-1 contingencies is required to provide an effective solution to DOCR coordination. This paper takes up the microgrid DOCR coordination problem by considering DG and line outages to provide a single set of DOCR settings those are good enough to set the DOCRs to operate for various possible network topologies.

A. Literature survey

DOCR coordination problem is a challenging task in presence of DGs. The influence of DGs in the distribution system is analyzed in [3]. In [3] it has also been said that SDGs have a considerable impact on fault current magnitudes compared to inverter-based DGs. Fault current limiters have been suggested in [2] to mitigate the impact of fault currents due to SDGs. . In [2] a dual configured microgrid protection coordination scheme using SDGs with FCLs is proposed which is solved heuristically using the genetic algorithm. New dual-setting characteristics are proposed in [4] and [5] which work effectively in microgrid environment and reduce the operating times of DOCRs. Keeping in mind that fault current varies along the length of the line, the coordination problem in [4] considers different possible fault locations along the line. To tackle the fault current deficit problem when inverter DGs exist in the microgrid, a time-voltage-current based inverse characteristics are proposed in [6]. In [7], microgrid protection coordination is achieved considering N-1 contingency. The coordination model in [7] is designed in such a way that all single line outage contingencies and DG outage contingencies are considered in the problem. GA-LP

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algorithm is developed [7] to solve the coordination problem. In [8], A hybrid GA algorithm is developed in which the constraints corresponding to different network topologies are considered. Interval programming (ILP) based formulation is developed in [9] to solve the relay coordination problem for various network topologies. A hybrid GA - ILP approach developed in [10] to solve the microgrid relay coordination problem for various fault locations. In addition to line outages, the connection and disconnection of DGs in the network will also affect the fault currents significantly. In this paper, an effective protection coordination model is developed which considers all N-1 contingencies along with constraints corresponding to various fault locations to solve the microgrid coordination problem. Keeping in mind the fact that fault current varies with the location of the fault, the proposed method also includes constraints sets corresponding to fault locations, which would complexify the problem and expect to fetch an effective set of DOCR settings which will be enough to operate for all network scenarios. The proposed coordination model is solved using a new hybrid heuristic optimization technique called invasive weed optimization - interval linear programming method (IWO-ILP). The IWO technique, proposed by Mehrabian and Lucas [11], is an effective probabilistic, metaheuristic optimization method which works based on the phenomenon of weed colonization (IWO). This technique has been successfully employed for ultra-wideband antenna design [12], [13]. The IWO technique is applied in [14] for the large-scale economic dispatch of generating units in power systems. The results of [12] show that the IWO technique works better than PSO, GA, and Differential Evolution (DE). In this paper, the pickup current settings (CPS) are fetched by the weeds in IWO and time dial settings (TDS) are obtained using ILP sub-problem. The coordination problem is designed with constraint sets corresponding to N-1 contingency including various fault locations (close in, far end, and 10 % distant on the line).

II. INVASIVE WEED OPTIMIZATION

A. Philosophy

The IWO algorithm is inspired by the concept of weed colonization which is an unwanted phenomenon in the agricultural fields. Weed is a plant, shrub or herb having a robust and adaptive characteristic whose vigorous and invasive habit of growth poses a serious threat to cultivated plants [11]. Sustainability, robustness, and variety are the main features of weeds which make them the most disturbing plants in the agricultural fields. Weeds have the habit of colonization by reproduction where there is an opportunity to grow, thus increasing their numbers and share the age, size of the neighboring plants. Each fully grown weed produces seeds which are dispersed in the field by nature (air, animals etc) and generate new weeds which again grow to flowering phase and produce more weeds and so on until weed colony is developed. The colonization stops when the colony reaches its maximum population limit which is constrained by resources availability. Survival and production of new weeds are decided by the individual fitness and better weeds are selected by competitive contest making them adaptive to the environmental conditions and improve over the number of generations.

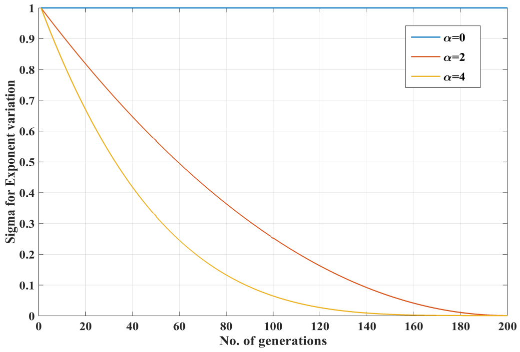

Fig. 1: Standard deviation chart of IWO.

B. Standard IWO Algorithm (IWO)

The important terms used to develop the IWO algorithm are explained below,

- Seed: Each valued optimization variable in the colony.
- Plant: Seed with evaluated worthiness.
- Colony: Number of seeds.
- Fitness: Calculated value which indicates the worthiness of each seed in the colony.
- Population: Number of plants in the colony.

Having defined the key terms used in the algorithm, the IWO algorithm for a minimization optimization problem is explained in the below process steps,

1) Population Initialization: Define minimum (S_{min}) and maximum (S_{max}) number of seeds in the colony and dispread the finite number (N) of seeds in the solution space randomly.

2) Ranking and Reproduction: Each dispreaded seed grows to a flowering weed plant and holds a fitness indicating its strength to survive in the competition. The plants are sorted according to their fitnesses i.e, the plants are ranked and allowed to produce new seeds depending on their fitness and best (F_{max}) and worst (F_{min}) fitnesses of the colony. The number of seeds produced by a plant in each iteration varies linearly with respect to the fitness of the respective plant. This is given by the expression,

$$S_p = \frac{(S_{max} - S_{min})}{(f_{max} - f_{min})} f_p + S_{min} \tag{1}$$

Where, S_p is the number of seeds produced by a plant 'p', and f_p is the fitness of the plant. Plants with better fitness indicate that they are adaptive to the field conditions and tend to produce more seeds. This is a crucial property in the algorithm which encourages all plants to take part in reproduction. Unlike reproduction (crossover) in GA, IWO encourages all weeds to participate in reproduction entrusting the fact that inefficient weeds can also carry useful information.

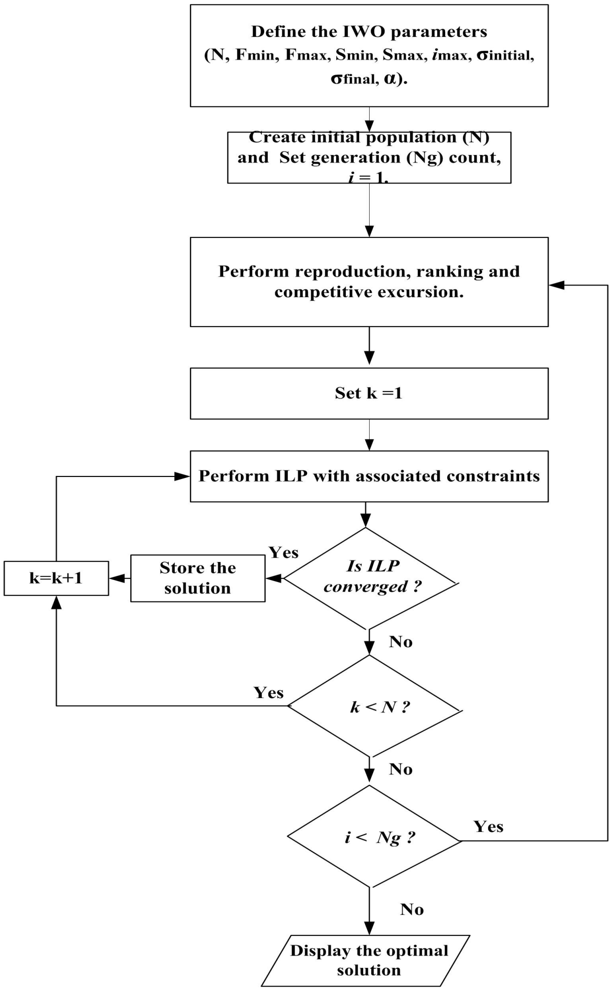

Fig. 2: Flowchart of the IWO-ILP algorithm

3) Spatial Dispersal: The generated seeds from reproduction are randomly distributed in the search space with the mean at parent plant position and variable standard deviation (SD). The standard deviation (SD), σ, is usually defined iteration wise and it is expressed by

$$\sigma_i = \frac{(i_{max} - i)^{\alpha}}{i_{max}^{\alpha}}(\sigma_{init} - \sigma_{final}) + \sigma_{final} \tag{2}$$

where i is the iteration count, i_{max} indicates the maximum iterations, σ_{init} and σ_{final} represents the initial and final standard deviations. α is the nonlinear modulation index. The excursion of σ for various α values is shown in Fig. 1.

4) Competitive Exclusion: Competitive exclusion is the process of eliminating the weeds with poor fitness such that only healthy weeds sustain to produce seeds for next generations. Once the number of weeds in the colony reaches the maximum value, all the seeds along with their parents are ranked and sorted once again. Those seeds with poor fitness shall be perished to achieve maximum colony strength. In each generation, the colony retains its maximum population by selectively excluding the weak weeds.

Those plants which survived the exclusion step shall produce new offspring and the cycle rotates again until maximum iterations are run.

III. INTERVAL LINEAR PROGRAMMING (ILP)

Many practical problems in real life those with uncertain parameters. This uncertainty is handled in many ways. One is to model these uncertainties as intervals. It is an elegant mechanism in which variables are defined as ”Uncertain but bounded”. The logical interpretation of traditional arithmetic is the interval arithmetic where variables are defined as real intervals (7) and (8) gives the traditional ILP formulation as given below:

$$min \;\; Z = (C^I)\,X \tag{3}$$

subjected to :

$$A^I\,X \le b^I, \;\; X \ge 0 \tag{4}$$

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

$$C^I = [\underline{C}, \bar{C}], C = C : \underline{C} \le C \le \bar{C} \tag{5}$$

$$A^I = [\underline{A}, \bar{A}], A = A : \underline{A} \le A \le \bar{A} \tag{6}$$

A standard LP formulation may be derived from (3)-(6) which gives solution to the standard ILP as give below,

$$min \;\; Z = (\bar{C} or \underline{C})\,X \tag{7}$$

subjected to :

$$\bar{A}\,X_1 - \underline{A}\,X_2 \le \underline{b}, \;\; X_1, X_2 \ge 0 \tag{8}$$

and,

$$X = X_1 - X_2 \tag{9}$$

A. Hybrid IWO-ILP Algorithm

Heuristic optimization methods do pose a high computation burden in terms of a number of iterations to converge to a feasible solution. This burden can be reduced and computational efficiency can be improved by hybridizing with traditional optimization techniques [8,10]. In this paper, one such hybrid method is proposed that is obtained by fusing IWO with Interval linear programming. This hybridization is inspired from the existing hybrid heuristic techniques [8,10]. The ILP is formulated as a subproblem to IWO wherein each generation, the weeds are tested for optimality, and if optimal solutions are obtained, such weeds are saved and ranked accordingly. In the competitive exclusion phase, the weeds fetching infeasible solutions are sorted and weak weeds are eliminated selectively. This hybridization procedure is similar to that in [10]. The number of generations is fixed and it is decided based on the number of trial runs. For the test system considered in this paper, it is observed that hybrid IWO-ILP method converged within 20 iterations to the optimal solution, which is much faster than IWO. The numerical evaluation is given in results and analysis in section VI. Fig.2 shows the complete flowchart of using hybrid IIWO method.

IV. OPTIMAL DOCR COORDINATION PROBLEM

The optimal DOCR coordination problem is a nonlinear constrained optimization problem with an objective of minimizing the DOCR operating times, designed to find the optimal values of TDS and CPS values such that all the coordination and limit constraints are satisfied The operating time of standard inverse DOcR is given as follows:

$$t_{if} = \frac{\alpha(TDS_i)}{\left(\frac{I_{if}^{fault}}{CPS_i}\right)^{\beta} - 1} \tag{10}$$

where i is the relay number, f is the fault location identifier, α and β are constants which are chosen based on the type of inverse characteristics. Here, α and β are taken to be 0.14 and 0.02 respectively. TDS_i and CPS_i are the time multiplier setting and current plug setting of i^{th} relay for a fault j^{th} location. I_{if}^{fault} is the fault current seen by i^{th} relay at f^{th} location. The objective function is defined as follows:

$$min\ \ Z = \sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{i=1}^{R}(t_{if}^{n} + \sum_{k=1}^{B} t_{kf}^{n}) \quad \forall\ (i,k)\ \in\ \Omega \tag{11}$$

where the group of all primary and backup relays is denoted by Ω, F denotes the number of fault locations, B is the number of backup relays for a i^{th} primary relay, k is the backup relay identifier. N is the set of all contingencies including microgrid operating modes. The values for t_{if}^{n} and t_{kf}^{n} can be obtained from (10). The associated constraints considered for each contingency are given below,

$$t_{kf}^{n} - t_{if}^{n}\ \geq\ CTI \quad \forall\ i,k,j \tag{12}$$

$$t_i^{min}\ \leq\ t_i \leq\ t_i^{max} \tag{13}$$

$$TDS_i^{min}\ \leq\ TDS_i\ \leq\ TDS_i^{max} \tag{14}$$

$$CPS_i^{min}\ \leq\ CPS_i\ \leq\ CPS_i^{max} \tag{15}$$

where t_i^{min} and t_i^{max} are the minimum and maximum operating times of i^{th} relay. [TDS^{min}, TDS^{max}] and [CPS^{min}, CPS^{max}] are the minimum and maximum limits on TDS, CPS respectively. CTI is the coordination time interval.

V. SYSTEM UNDER STUDY AND SIMULATION SETUP

The proposed coordination model is tested on the Canadian Urban Benchmark distribution system [2,3] shown in Fig. 3. This system is a two 4-bus feeder system rated at 8.7 MVA with 0.1529+j0.1406 Ω/km line impedance. Four synchronous based DGs are connected at 4, 5, 6 and 9 buses of the system. Each DG is of 5 MVA capacity, with 10% transient reactance. The CT ratio is considered to be 2000:1 for all relays. The completed details of the system can be found in [2].

The coordination model is tested in three cases as given in Table I. In case I, the coordination problem is formulated using the main topology conditions [2]. In model II, constraints corresponding to N-1 contingencies in grid-connected mode are included in the coordination problem. In case III, the constraints corresponding to the islanded mode of microgrid are also included in the coordination model.

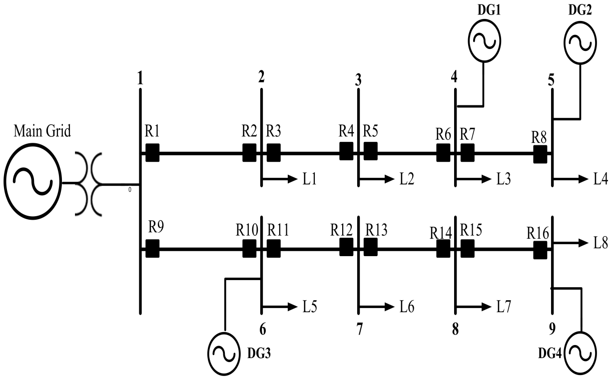

Fig. 3: 9 bus microgrid test system

TABLE I: Different cases of simulation

Case	Description
case I	grid connected topology (GCT)
case II	GCT+ (N-1) contingecy
case III	GCT+(N-1) contingency+ Islanded topology (IST)

VI. RESULTS AND ANALYSIS

A. Advantage of ILP formulation

Each case of the proposed coordination model considers a set of constraints posed corresponding to (12)-(15). Since the modeled coordination problem has set of linear inequality constraints corresponding to each contingency, it is convenient to convert such a constraint set of each primary/ backup DOCR pair to an interval constraint, such that the uncertainty in each constraints' coefficients which happen due to different

TABLE II: OPTIMAL TDS AND CPS SETTINGS OF 9 BUS SYSTEM

Relay	case I		case II		case II	
	TDS	CPS	TDS	CPS	TDS	CPS
R1	0.1000	0.5420	0.0880	0.3316	0.4469	0.3285
R2	0.1000	0.6433	0.0929	0.2238	1.5385	0.3295
R3	0.1000	0.5063	0.0735	0.3676	2.2027	0.3839
R4	0.1000	0.5262	0.0575	0.5382	1.9899	0.3097
R5	0.1000	0.5077	0.050	0.4851	1.6629	0.1939
R6	0.1140	0.3317	0.1163	0.2422	1.2954	0.2230
R7	0.1000	0.2847	0.050	0.3217	1.3476	0.0988
R8	0.1000	0.3132	0.0690	0.2955	1.6403	0.1695
R9	0.1000	0.5774	0.050	0.4635	2.3797	0.3746
R10	0.1000	0.4495	0.0981	0.2883	2.2776	0.2802
R11	0.1000	0.1629	0.0502	0.2762	0.7205	0.3140
R12	0.1481	0.1024	0.0601	0.2725	2.2864	0.3184
R13	0.1000	0.2077	0.050	0.5498	0.6145	0.3443
R14	0.1053	0.1377	0.0878	0.1316	2.2094	0.2052
R15	0.1000	0.3171	0.0652	0.3189	1.5339	0.3742
R16	0.1000	0.2500	0.0651	0.3192	0.4106	0.3825
OF (sec)	117.91		161.32		201.19	

TABLE III: PRIMARY AND BACKUP RELAY OPERATING TIMES FOR CLOSE IN FAULTS IN CASE I

B.R	P.R	$I_{fb}(KA)$	$I_{fp}(KA)$	t_b (sec)	t_p(sec)
R10	R1	2417.61	6443.58	0.7062	0.4003
R4	R2	2312.73	6038.33	0.9687	0.4648
R10	R3	2286.58	6038.21	1.0332	0.3995
R6	R4	2341.75	5659.28	0.6601	0.4250
R3	R5	2312.73	5659.39	0.9189	0.4159
R8	R6	1166.62	5306.96	1.2510	0.3773
R5	R7	2341.75	6905.97	0.9030	0.2743
-	R8	-	1580	-	0.7484
R2	R9	2286.58	6299.76	1.3883	0.4216
R12	R10	1184.86	5906.23	0.5831	0.3805
R9	R11	2417.61	7480.92	0.9506	0.2221
R14	R12	1210.45	6910.34	0.4932	0.2908
R11	R13	1184.86	6910.46	0.5386	0.2489
R16	R14	1237.61	6393.53	0.7708	0.2327
R13	R15	1210.45	6392.94	0.6519	0.3060
-	R16	-	1570.5	-	0.5961

B.R: backup relay; P.R: primary relay;

TABLE IV: COORDINATION VIOLATIONS FOR N-1 CONTINGENCIES FOR 9 BU SYSTEM

Topology / Outage	case I	case II	case III
GCT	0	0	0
DG1	3	0	0
DG2	3	0	0
DG3	4	0	0
DG4	2	0	0
L1-2	2	0	0
L2-3	2	0	0
L3-4	4	0	0
L4-5	2	0	0
L1-6	2	0	0
L6-7	4	0	0
L7-8	2	0	0
L8-9	2	0	0
IST	8	7	0
Total	40	7	0

contingencies are taken into account. For example, in case I the coordination model has N_c coordination constraints represented by (12), N_t limit constraints represented by (13), and N_{set} limit constraints represented by (14) and (15). So, a total of ($N_T = N_c + N_t + N_{set}$) constraints are to be included for each fault location in grid-connected topology. For F fault locations, there will be a total of $F \times N_T$ constraints to be solved for each case. However, by formulating the coordination model as ILP each of $F \times N_c$, $F \times N_t$, $F \times N_{set}$ N_c can be represented as interval sets and reformulated as N_c, N_t, N_{set} constraints respectively. So, the total number of constraints to be handled using ILP are N_T instead of $F \times N_T$. This greatly reduces the computational burden and execution time. The proposed coordination model deals with N_T of 80, 696, and 760 coordination and limit constraints in case I, case II and case II respectively. The coordination model defined by (11)-(15) are reformulated in the form of (3)-(6) as ILP and converted to standard linear programming problem using (7)-(9). The results are presented in subsequent sections.

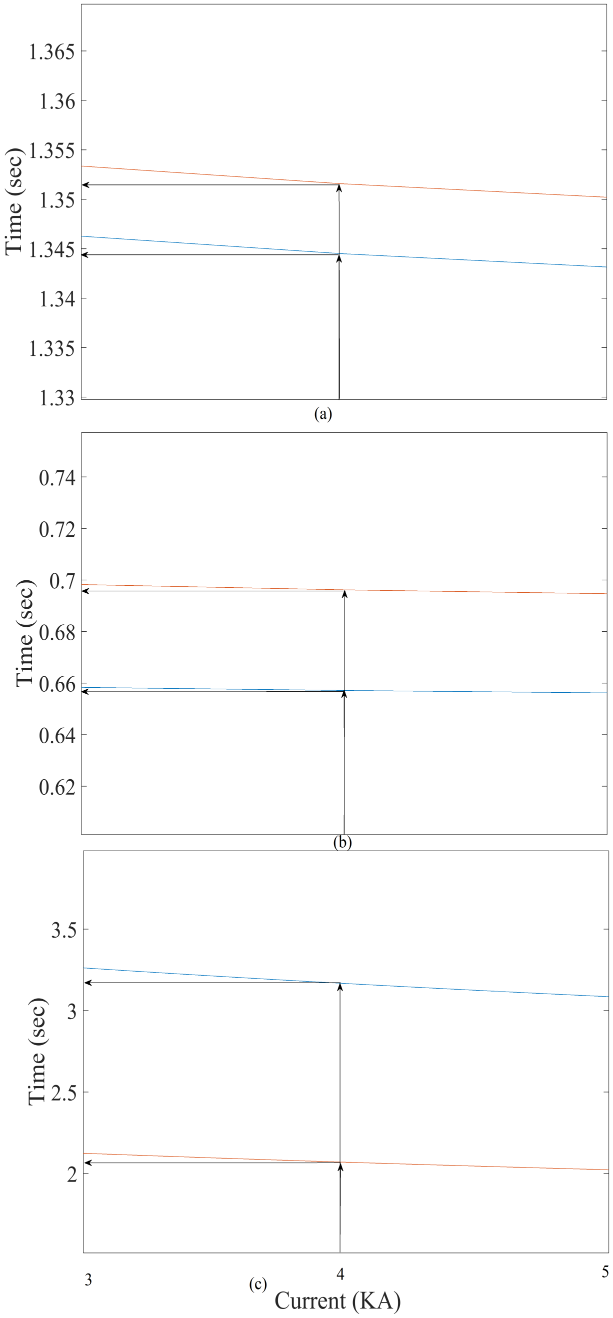

Fig. 4: current-time curves relays R5 and R3 for (a) case I, (b) case II, (c) case III

B. Results of the test system

The optimal settings obtained for all the 16 DOCRs of the test system are given in Table II. As each case of the proposed coordination model works with different N_T constraints, the optimal settings are, obviously, different in each case. The upper and lower limits of TDS are taken to be 0.05 and 2.5 respectively and CTI is taken as 0.2 sec. The CPS limits are taken as $1.25 * I_{load,max}$ and $(2/3) * I_{fault,min}$ respectively. The CPS values given in Table II are the per unit values at a

CT ratio of 2000:1. Since the N_T constraints of case I is less than that of case II and case III, the value of Z(sec) is less in the case of case I. The Z in case II is 161.32 sec which is 36.8% increase compared to case I. Similarly in case III Z has an increase of 70.6% in value compared to case I.

C. Coordination violation Analysis

The robustness of the obtained solution is tested by checking the coordination constraints of all DOCR pairs across all contingency cases. As an illustration, Table II shows the DOCR operating times of the test system for close-in faults in grid-connected topology (GCT). The corresponding fault currents seen by the backup relays($I_{fb}(KA)$) and the fault currents seen by the primary relays (I_{fp} (KA)) are also given in columns 3 and 4 of Table III. t_p and t_b are the primary and backup DOCR operating times. From this table, it can be observed that all primary/backup relay pairs have good coordination margin of at least CTI. The summary of the coordination analysis is presented in Table IV. The second column of Table IV shows the coordination violations when the optimal settings in case I are applied and tested for various contingencies (column 1 of Table IV). It can be observed that for GCT there are no coordination violations whereas, for other contingency cases, violations are recorded. When the optimal settings of case II are applied for various contingencies, all the contingencies except for IST are observed to fetch zero violations. This is obvious as case II does not take into account the N_T constraints of IST topology. However, for case III where the proposed coordination model takes into account N_T constraints corresponding to all N-1 contingencies including IST, no coordination violations are recorded for this case which emphasizes the effectiveness of the proposed method. However, it can be seen that Z for case III is very high as compared to that of the case I and case II. So, it can be said that optimal coordination is achieved for N-1 contingency at an expense of higher DOCR operating times. An illustration of the effectiveness of the proposed method is shown in Fig.4 which shows the current-time curves of DOCRs R5 and R3 for the case I, case II, and case III for IST topology. As discussed earlier IST has coordination violations for the case I and case II, this R5-R3 relay pair fail to coordinate for the cases I and II. from Fig.4(a) and 4(b) it is clear that the CTI is less than 0.2 sec. In case III, where IST coordination violations are nullified, the optimal settings of R5 and R3 are such that they achieved good coordination margin (CTI $>$ 0.2 sec) as shown in Fig.4(c).

VII. CONCLUSION

The optimal coordination of DOCRs considering line and DG outages including various fault locations for microgrids is discussed in this paper. The coordination model which considers all the constraints corresponding to N-1 contingencies is developed. The coordination problem is formulated as an interval programming problem to reduce the redundancy of repeated constraints. The ILP problem is stated as a sub-problem to IWO heuristic optimization algorithm to obtain a robust solution. ILP eliminates the weeds with weaker fitness thus providing the optimal solution in a faster way with less number of generations. The developed model is tested on 9 bus microgrid system in three cases and results are presented. The results show that the optimal DOCRs settings can be achieved which are fit for different microgrid topologies and possible contingencies.

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