A New Approach for the Setting of Directional Overcurrent Relays by Incorporating Cascading Outages

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Abstract

Directional overcurrent relays (DOCRs) are the essential protective devices in distribution networks which are usually set without considering any contingencies. However, the current challenge in power systems is the existence of uncertainty and its unfavorable consequences. It sometimes appears that some elements simultaneously fail which makes other parts to be overloaded to the extent that it leads to cascading outages. Therefore, DOCRs may have mal-operation which ends in unwanted trips when there is no fault, or they may not operate in the case the fault is located within their reach point. In such cases, the coordination setting will need complex programming with many related non-linear inequality constraints. In this paper, a novel hybrid method is proposed based on multi-objective optimization including new objective functions by using the genetic algorithm (GA). Also, the cascading outages are considered in the presented method based on network data analysis. This approach is performed on distribution part of the IEEE 14-bus meshed system, and a real industrial radial feeder named TOSEE, located in Iran. The simulations have been implemented in MATLAB and PowerFactory-DIgSILENT software packages in different models, and the results are evaluated.

Keywords: Directional overcurrent relays; Distribution networks; Uncertainty; Cascading outages; Multi-Objective optimization; Genetic algorithm.

1. Introduction

The primary aim of using directional overcurrent relays (DOCRs) in distribution networks is to detect the permanent faults and clear them through line sectionalizing by using the circuit breakers (CBs). Due to proper operation and low expenditure, the DOCRs are the main protection devices in distribution networks. The decision variables of DOCRs are the pickup current (*Ip*) and time multiplier setting (TMS). In a microprocessor-based DOCRs, TMS changes continuously (due to the manufacture advancement of the relaying devices), and this has a vital effect on the relays' operation time, and *Ip* has discrete values which are proportional to current transformer ratio (CTR).

The optimization methods which have inherent advantages are employed to designate the valid values of the protection coordination problem (PCP) [1, 2]. As the conventional methods have low convergence speed and low accuracy, they are no longer utilized [3].

Various optimization methods have been introduced to determine the decision variables of DOCRs. In [4], the decision variables were obtained by executing mathematically-based optimization processes in GAMS software. On the other hand, the TMS values were attained in [5] by applying linear programming assuming identified *Ip* values.

Recently, the optimization algorithms based on intelligence which are inspired by nature have been recommended for improving the efficacy of the method [6]. Consequently, both *Ip* and TMS values were arrived at in [7, 8] through the genetic algorithm (GA) by considering PCP as a non-linear programming. Alternatively, in [9, 10], PCP was formulated as a mixed non-linear integral problem regarding the discrete values of the pickup current and the non-linear nature of the DOCRs' equation. Thus, this problem was solved using meta-heuristic optimization algorithms such as hybrid GA and Particle Swarm Optimization (PSO) in MATLAB software.

Besides, an enhanced protection coordination scheme has been proposed in [11] utilizing dual time-current characteristics (DTCCs) for overcurrent relays which are followed by two inverse-time curves in series. These characteristics are fulfilled by numerical DOCRs incurring investment costs. Therefore, a techno-economic optimal replacement model is devised to attain a least-cost numerical DOCRs deployment plan while eliminating mis-coordination and minimizing total operation time of the relays. The proposed model constitutes a mixed integer non-linear programming (MINLP) problem which is solved with sine-cosine algorithm. Furthermore, Ref. [12] optimizes different issues of overcurrent relays in micro-grids. Two cases are taken for each relay, with single variable (time dial settings (TDS)), with two variables (TDS and pick up current setting (*Ip*)). An objective function that minimizes the total operating time of all primary relays has been regarded. A GA is employed for the optimization purpose which exhibits better performance than the other conventional algorithms.

The conventional protection approaches are based on the fixed network topology [9]. However, the network topology may be altered following the maintenance or contingencies (including transient and permanent faults) or the operator's mistake. The contingencies such as line outage, distributed generation (DG) outage, and disconnection of sub-transmission network (islanding mode) increase the number of constraints that are likely to be violated, and this complicates the solution algorithm [13]. In [14, 15], the decision variables were obtained for PCP in the sub-transmission network by considering all topologies derived from lines outage. Also, it happens sometimes that some power devices simultaneously fail and this leads to cascading outages turning into a blackout. Although the likelihood of such an event is low, it may happen and result in substantial financial damage [16]. As an example, there were blackouts in Europe on November 4, 2006, and in India on July 30-31, 2012 [17, 18]. Besides, it is estimated that annually more than 10 million people are incurred with financial damage due to the power grids uncertainty [19]. Therefore, it should be appropriate to consider simultaneous contingencies in the DOCRs setting so that the network does not experience a vital interruption.

Up to now, the previous studies have not considered cascading outages through multi-objective optimization method (MOOM). The MOOM includes new objective functions (OF_S) which are capable of solving PCP with the minimum violated constraints.

Moreover, the penetration of the DGs into power systems is growing which affects the operation of distribution networks. Hence, by considering DG, the problem formulation should be extended. The employed DGs usually have synchronous generator types which have more impact on the network short circuit level (SCL) compared to the inverter-based ones [20]. Synchronous-based DGs (SBDGs) are more susceptible to power grid faults regarding their low inertia time constants. Ref. [21] paper proposes communication-assisted dual-setting DOCRs as effective solutions for providing fast-response protection in order to meet transient stability constraints of SBDGs in micro-grids.

In this paper, a novel hybrid method has been introduced for the protection coordination of DOCRs by employing the MOOM, which involves new OF_S. Moreover, all the cascading outages are investigated into different models, and the decision variables are obtained for each of them. The uncertainty within the power system is a challenging issue in the coordination problem that requires complex programming with many related non-linear constraints. Therefore, one of the most critical aims is that the maximum number of these constraints should be satisfied. Unlike the current protection coordination methods, the present approach obtains decision variables by incorporating network data analysis and the GA with the purpose of optimizing the *OFs* by seeking the best potential solution. The proposed approach is implemented on TOSEE radial feeder and the IEEE 14-bus system by incorporating DGs via PowerFactory-DIgSILENT and MATLAB software packages.

The outstanding features of this paper can be outlined as the following:

- Solving the PCP based on MOOM;
- Considering the cascading outages;
- Defining new objective functions for PCP;
- Applying the proposed method on a real distribution network in addition to the IEEE 14-bus system.

2. Problem formulation

2.1. Relay's characteristic

The DOCRs have numerous characteristics which have been investigated in the literature by employing standard Inverse Definite Minimum Time overcurrent relay (IDMT) curves. Here, a non-linear one is recommended based on the IEC standard with a standard inverse (SI) tripping curve as the following (1):

$$t_i = \frac{0.14}{\left(\frac{Isc}{Ip}\right)^{0.02} - 1} \times TMS \tag{1}$$

Where:

t_i is the i^{th} relay's operation time for a fault close to CBs, and Isc is the short circuit current passing through the i^{th} relay.

2.2. Problem constraints

The protection coordination problem is subjected to some constraints which are described in the following.

2.2.1. Coordination time interval (CTI)

As shown in Fig. 1, to have a time interval between the operation of the main relay (Rm) and its backup relays (Rb^1, Rb^2 ... and Rb^n), the CTI is considered. The backup relays function only in the case of failure in the operation of the main relay. The CTI ensures the permanence of the protection coordination and the network's safety. The value of CTI is assumed 0.3 seconds in equation (2) by taking into account some factors such as the relay overshooting, CBs' interrupting time, and reliability of the network [22]. In (2), t_i^b and t_i^m are the main and backup relays' operation time, respectively. For each backup relay in the network, equation (3) must be satisfied. The relevant constraints can be expressed as follows:

$$\Delta tmb = t_i^b - t_i^m - CTI \tag{2}$$

$$\Delta tmb \geq 0 \tag{3}$$

Place of Fig. 1

2.2.2. The pickup current bounds

The pickup current is limited to a particular range in equation (4) by taking into account the current transformer (CT) ratio (0.5, 0.6, 0.8, 1, 1.5, 2, and 2.5) [13]. The fundamental concern in the protection of lines is that no line should be out of service due to the mal-operation of DOCRs. Therefore, Ip must be larger than the maximum load current in equation (5), and the load flow is executed by incorporating the peak load of the network. Moreover, relation (6) ensures that DOCRs distinguish all the faults that occur in their reach point and detect the lowest short-circuit current (Isc_{min}). However, in some particular condition, the fault current is less than the maximum load current, and relation (6) leads to load interruption when there is no fault in DOCRs' reach point. Thus, relation (5) is preferred to (6) as the load of power grid should not be sacrificed for detection of this fault. This type of fault is named high-impedance fault. Therefore, the priority in the distribution networks is the loads' reliability and the reduction of interruption duration which can increases the consumers' satisfaction [23].

The bounds of Ip are defined as follows:

$$Ip_{min} < Ip < Ip_{min} \tag{4}$$

$$Iload_{max} < Ip \tag{5}$$

$$Ip > Isc_{min} \tag{6}$$

2.2.3. TMS bound

The value of TMS is assumed as continuous, and it is directly proportional to the relay's operation time based on the relay's characteristic. According to (7), this variable is defined within a lower and upper boundary between 0.05 and 1 for all of DOCRs.

$$TMSmin < TMS < TMSmax \tag{7}$$

2.3. Objective functions

The OF_S must be such that all or most of the constraints corresponding to the protection coordination are satisfied and there is no mis-coordination in the operation of the DOCRs. In this method, PCP is solved by taking into account the multi-objective optimization, which involves four new objective functions, OF_A, OF_B, OF_C, OF_D according to functions (8)-(11). It should be noted that these *OFs* have not been used in the previous studies. The problem formulation aims to optimize all of them such that the best possible solutions are achieved simultaneously for each of *OFs*. Also, Square brackets (i.e., [ ]) are used to denote the floor function, which rounds a real number down to the next integer (as in [π] = 3, in [-π] = -4).

- OF_A

  Mis-coordination between the main relay and backup relays violates equation (3) (Δtmb <0), and OF_A becomes large due to the high value assigned to α. In this condition, the proposed algorithm will eliminate these chromosomes (decision variables) in the next generation until the best values are obtained. Moreover, this function tries to decrease the overall operation time (i.e., $\sum_{i=1}^{NR} t_i$).

- OF_B

  Similarly, an improper *TMS* value (i.e., *TMS* >1) has a significant effect on PCP which is penalized by OF_B.

- OF_C

  If the current passing through the main relay (Ip^{Rm}) is remarkably higher than its backup relay's current (Ip^{Rb}) (i.e., $Ip^{Rm} \geq 2 \times Ip^{Rb}$), the protection coordination is not reasonable due to the high value yield for Δtmb ($\Delta tmb \gg 0.3$). Therefore, OF_C is used for resolving this problem such that these chromosomes are not generated in the next iteration (generation).

- OF_D

  Also, if the fault current is very close to *Ip* of the DOCRs (i.e., $Isc \leq Ip \times 1.6$), it is not adopted for the protection coordination due to the higher operation time attained for DOCRs. Consequently, OF_D is employed to solve such problems.

$$OF_A = \alpha \times \left(\left\| \left[\frac{|\Delta t_{mb}|}{1.1 \times \Delta t_{mb}} \right] \right\| \right) + \sum_{i=1}^{NR} t_i \tag{8}$$

$$OF_B = \alpha \times \left(\left[TMSi \right] \right) ,\mathrm{i} = 1, \ldots, \mathrm{NR} \tag{9}$$

$$OF_C = \alpha \times \left(\left[\frac{Ip^{Rm}}{Ip^{Rb} \times 2} \right] \right) \tag{10}$$

$$OF_D = \alpha \times \left(\left[\frac{Ip \times 1.6}{Isc} \right] \right) \tag{11}$$

In (8)-(11), NR is the number of DOCRs. The parameter α is a weighting coefficient which is determined experimentally by trial and error. In this regard, a specific value of α may result in the increase of relay's operation time while it brings about the decrease of mis-coordinations. Therefore, the considered α should promise between decreasing operation time of the relays and decreasing mis-coordinations among them. Regarding this issue, the value of α has been considered equal to 500 in this paper. Besides, the reason that α is the same in all the objective functions is that all these four OFs have the same weighting to have equal effects on the problem. It should be noted that we can leave determination of α's value to the optimization algorithm. In part 4.5.1, this issue will be regarded, and the coefficients will be optimized along with the objective function.

3. The proposed approach for solving protection coordination

The algorithm for determining decision variables of DOCRs in the distribution networks is formed as a non-linear programming. All the related constraints must be observed to acquire optimum values. The GA as a robust approach to optimization problems is employed to solve such a non-convex problem based on the generation of elite descendants. The decision variables are encoded within a collection of genes composing the chromosome. The GA generates a set of chromosomes which are known as a population. The initial population is randomly generated such that the maximum number of problem constraints are satisfied. All the generated chromosomes are chosen through selection, cross-over, and mutation operators for producing the next generation, and those having the most appropriate OF_S are preferred to be present in the next iteration. The full description of the GA is given in [24]. As seen in Fig. 2, the flowchart of the suggested method is divided into three sections.

- *First section*

  At first, the values of Ip are determined by incorporating the network peak load and CTR. Further, the fault current is calculated for all the main and backup relays according to the fault close to the CBs (i.e., network data analysis).
- *Second section*

  Then, the TMS values encoded in the chromosomes of the GA are generated based on MOOM. In the case of a single-objective optimization problem, the solution aims to promote a performance index reflecting the quality of the solution by minimum or maximum objective function (*OF*). However, sometimes due to the non-linear nature of the problem, we can consider several OF_S and optimize the values of them simultaneously for pursuing the best possible results. In each iteration of section 2, OF_A and OF_B are evaluated, and among the TMS values, those having the best values are selected for the next step.
- *Third section*

  In the third section of algorithm, based on the current settings obtained from the previous section, the new values of current and time settings are generated by the GA algorithm. In this way, the obtained current settings fall in a proper range based on their lower and upper bounds, and the new values are produced by the GA, i.e., the TMS and Ip values attained from sections 1 and 2 are considered to be on a chromosome, and the final fitness values are obtained based on MOOM with all OF_S (OF_A, OF_B, OF_C, OF_D) by seeking the best potential solution.

The process continues in this manner until the required iterations are completed.

Place of Fig. 2

4. Numerical studies

In this part, the proposed approach for PCP is applied on two case studies in different models. The first case study is the distribution part of IEEE 14-bus system and the second one is a real distribution network. Both case studies have DGs that participate in supplying loads of the system. The IEEE meshed system and TOSEE feeder have sixteen (R1, R2,…, R16) and four (Ra, Rb, Rc, Rd) DOCRs, respectively, for all of which the TMS and *Ip* values must be calculated. As mentioned earlier, the GA has been employed for the optimization purpose. The parameters of the employed GA in this paper are as Table 1. It should be noted that these parameters have been tuned by trial and error through several executions of the GA to obtain the best results.

Place of Table 1

4.1. The IEEE 14-bus system

The first case study, shown in Fig. 3, is the distribution part of IEEE 14-bus system as a micro-grid. The under-study area has been distinguished by dashed lines within the whole system. The system's data are given in [25]. This network is connected to a sub-transmission network via two 132kV/33kV transformers having the capacity of 60MVA. Three 10MVA synchronous-generator-type DG units are also connected to this grid. Each DG unit is composed of 10 parallel small DGs having a rated capacity of 1MVA. The technical data of these DGs are given in Table 2. The CTR values are also shown in Table 3.

Place of Table 2

Place of Table 3

Place of Fig. 3

4.2. Real industrial radial feeder of TOSEE

Besides the IEEE 14-bus system which is a meshed network, a real industrial radial feeder named TOSEE is also considered as Fig. 4. This network is one of the outgoing feeders of 63kV/20kV Koushkan substation located in Zanjan City, Iran. The total load of this system is 17.25MVA as 15.35MW and 7.41MVAr, respectively. This radial feeder is connected to the sub-transmission network via two 40MVA transformers. It is assumed that the network has three DGs with the capacity of 2MVA. The CTR values for all the employed DOCRs are 1000:5.

Place of Fig. 4

4.3. Simulation results

This part presents the simulation results including optimal setting values of DOCRs based on multi-objective optimization with considering all the cascading outages models (given in Table 4) for the IEEE 14-bus system and TOSEE feeder. The problem formulation investigates all the topologies resulted from every model. For example, in the case of DG outage, the relay must support all the currents flowing in the network resulted from the outage of all three DGs. Also, the current setting value in the first part of the problem has been obtained in terms of maximum current of all the variable topologies. In the other words, among the outage of three DGs, the one leading to higher current flow in the line has been considered for setting of the relay. Moreover, all models involve different particular constraints that must be taken into consideration in the protection coordination programming. The optimal values of decision variables for all DOCRs are obtained as Tables 5 and 6, respectively for the IEEE 14-bus system and TOSEE radial feeder. Also, the total operation time related to each cascading outage for both case studies is demonstrated in Table 7.

The results for PCP are different for the two networks due to the configuration of these systems (i.e., one is radial, and the other one is meshed). As a result, the optimal values obtained for TMS in the IEEE 14-bus network are higher than those for TOSEE feeder. Further, the number of constraints for the radial feeder is more than that for the IEEE system (due to the difference in the dimension of the two networks); however, most of them are linear and solving them is straightforward. It must be noted that, when the network topology has a significant outage, the problem constraints are severely changed and become more non-linear. This issue has a substantial impact on the results leading to noticeable reduction in the relay’s operation speed. As a result, in models with substation outage, it seems that the fault current is hugely lower than the condition that the network is grid-connected. Consequently, the relay operation time increases dramatically. Therefore, the overall operation times shown in Table 7 which are obtained for models 1, 2, 5, and 6 are longer than the values obtained for models 3, 4, and 7. This happens due to the network SCL, so that the fault current passing through DOCRs is inversely proportional to the relay’s operation time; which in turn, stems from the relay’s characteristic curve. Also, the number of problem constraints in models 4 and 7 is higher than that recognized in models 3 and 5 (due to the higher number of lines), but the problem formulation is more comfortable because of the reasons outlined above (i.e., the linear constraints).

In the islanding mode, the number of non-linear constraints becomes too many which makes the problem formulation extremely more complex. Moreover, in the islanding mode, there is a significant reduction in SCL that if not considered, it may lead to instability in the power system.

In TOSEE feeder, as there is only one feeding substation, not only model 1, but also models 2, 5, and 6 lead to islanding mode. As a result, the overall operation time of these models is more than that of model 1 (due to 2 or 3-case outages).

Since the fault currents for models 2 and 5, on the one hand and 3 and 7, on the other hand, are very close to each other, the DOCRs' operation times experience only a trivial difference. Furthermore, model 4 has the fastest reaction time of DOCRs to the fault current, because there is no loss of power source (DGs or substation) in this model.

Place of Table 4

Place of Table 5

Place of Table 6

Place of Table 7

4.4. Investigating the violated coordinations

The purpose of this section is to specify the number of mis-coordination occurring as a consequence of solving the PCP. The coordination constraints for DOCRs are considered to be violated when the backup relays operate with a time interval less than 0.3 seconds relative to the main relay (by taking CTI into account). Table 8 shows the number of violated coordinations in each investigated model for the IEEE 14-bus network and TOSEE feeder. It should be noted in both case studies, when DOCRs are set based on models 1 and 2, it supports all topologies in Table 4. Consequently, in the case of such events, the network loses a considerable generation, and if this issue is not taken into account, it leads to an increase in the number of mis-coordinations which ends into cascading outages. However, models 5 and 6 performed in the IEEE 14-bus system have 5 and 4 violations, respectively. Similarly, models 5 and 6 applied to TOSEE feeder both have 2 violations. By simplifying the variations of the network topology in models 7 and 4, there are the fewest number of mis-coordinations in both networks because the SCL varies gradually.

It is also observed that the number of violated coordinations for the IEEE 14-bus network is more than that for TOSEE feeder because a higher number of DOCRs are employed in the meshed system and there are higher SCL variations. Finally, if the PCP is set based on the severe outages, it results in an appropriate setting for all the topologies but with a higher operation time.

Place of Table 8

4.5. Single Objective optimization

4.5.1. Single Objective optimization with optimized *OF*s coefficients

In this part, for more investigation of the problem, the other aspects like single-objective optimization and optimization of objective function's coefficients are regarded. For this aim, the objective function of Ref. [26] is considered as equation (12). The relay operation curve is according to the IEC standard inverse-time with the same coefficients. Also, all the coordination procedure is done based on near-end of the fault point to all main relays. However, to more evaluate the problem, the coefficients of objective function (weighting factors of $\alpha, \gamma_1, \gamma_2$) will be optimized by the GA.

$$OF = \sum_{d\in D}((\alpha \times \sum_{i\in I}(t_i)^2) + (\gamma_1 \sum_{k\in K} e^{\gamma_2|\Delta t_{k,d}|}) + (\beta \sum_{k\in K} BC_{k,d})) \qquad (12)$$

Where *i* and *k* indicate all relays and all main and backup pair relays, respectively. Moreover, *I* and *K* represent the sets of all relays and main and backup pair relays, respectively. Further, *d* is the indices of fault points, and *D* represents the set of fault points. In addition, *BC* is a binary coefficient that is 1 when the coordination constraint is violated, and is 0 otherwise.

According to Table 9, it is observed that the sum of operation time of relays is 11.778s which shows a relative increase compared to multi-objective optimization. However, the number of mis-coordinations has remained one case. This shows the capability of the above objective function and its new idea in finding the weighting coefficients using the GA. It should be noticed that by increasing the mis-coordination, the value of *β* is accordingly increased which decreases the number of violated constraints. The values of objective function's coefficients has been obtained as Υ_1=112.567, ϒ2=108.421, and α=10.013 by the GA. The obtained results for model 4 of the IEEE 14-bus system are as follows:

Place of Table 9

4.5.2. Convergence of the proposed method in comparison with single-*OFs*

The convergence trend of the presented method for both case studies is investigated based on MOOM and the *single-OF*. In the single-objective function, all the introduced *OFs* are considered according to equation (13) so that the related constraints are not violated in the absence of these *OFs*, and only, the effect of multi-objective optimization and efficiency of the proposed method is observed. As the islanding mode is the most hazardous event for both systems, model 1 for the IEEE 14-bus network and model 2 for TOSEE feeder have been chosen for the comparison.

As shown in Fig. 5, when the problem formulation in the IEEE 14-bus system is based on MOOM, the overall operating time declines by 23% from 51.15 to 41.567 seconds. Also, according to Fig.

6, the DOCRs' operation time in TOSEE feeder decreases from 12.281 to 8.621 seconds which shows a 42% drop. This reduction in operation time is a considerable value when using MOOM. Furthermore, the effect of MOOM on TOSEE feeder is more than that of the IEEE 14-bus system which is due to the radial structure of the network and the fewer number of non-linear constraints.

$$single - OF = OF_A + OF_B + OF_C + OF_D \tag{13}$$

Place of Fig. 5

Place of Fig. 6

5. Conclusion

The protection coordination of DOCRs is complex and non-linear problem. In the current paper, a new method is proposed based on multi-objective optimization with new objective functions by using the GA. Furthermore, the cascading outages have been taken into account in the problem formulation. The simulation results demonstrate that considering MOOM and its new OF_S satisfy the problem constraints and increase the operation speed of DOCRs. Provided the multi-objective formulation of PCP, the obtained results for the decision variables (i.e., TMS and *Ip*) seem to be the best possible values for all of the relays. The proposed method is applied to the IEEE 14-bus system and a real industrial radial feeder by taking the cascading outages into account. When DOCRs are set having severe outages in mind, they become suitable for all the single or simultaneous contingencies that may occur. This can help maintain the network security.

Acknowledgment

The authors acknowledge the support of Hamed Zandi who provided help during this research.

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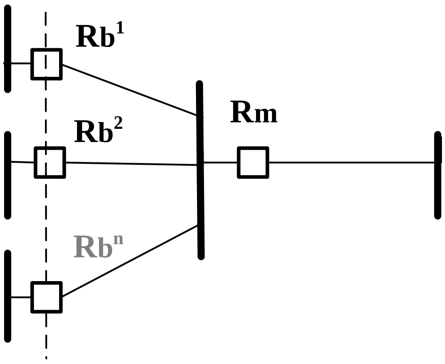

Fig. 1

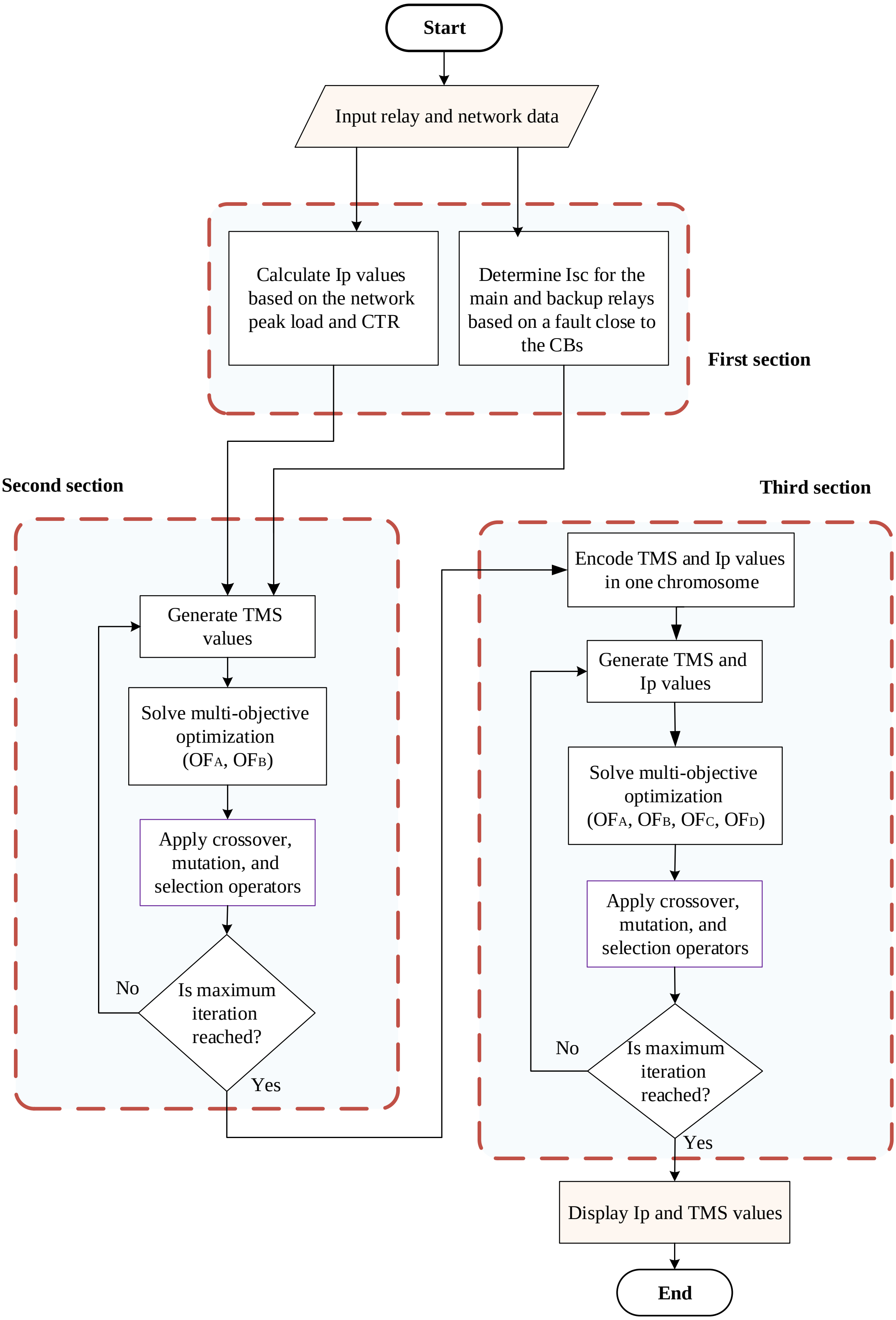
Start
Input relay and network data
Calculate Ip values based on the network peak load and CTR
Determine Isc for the main and backup relays based on a fault close to the CBs
First section
Second section
Third section
Generate TMS values
Solve multi-objective optimization (OFA, OFB)
Apply crossover, mutation, and selection operators
Is maximum iteration reached?
No
Yes
Encode TMS and Ip values in one chromosome
Generate TMS and Ip values
Solve multi-objective optimization (OFA, OFB, OFC, OFD)
Apply crossover, mutation, and selection operators
Is maximum iteration reached?
No
Yes
Display Ip and TMS values
End

Fig. 2

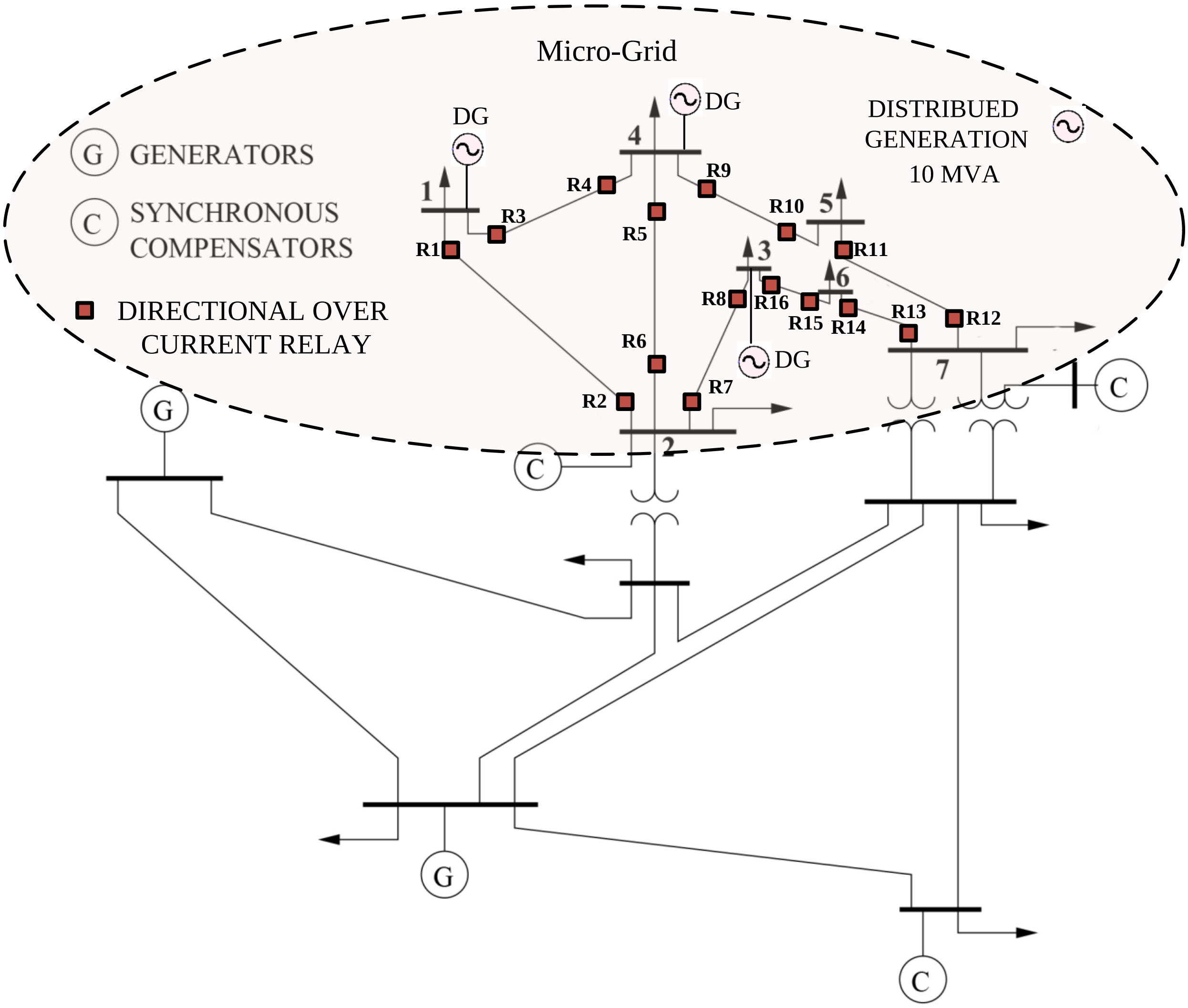
Micro-Grid
G GENERATORS
C SYNCHRONOUS COMPENSATORS
DIRECTIONAL OVER CURRENT RELAY
DISTRIBUED GENERATION 10 MVA
DG
DG
DG
1
2
3
4
5
6
7
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R13
R14
R15
R16
G
G
C
C
C

Fig. 3

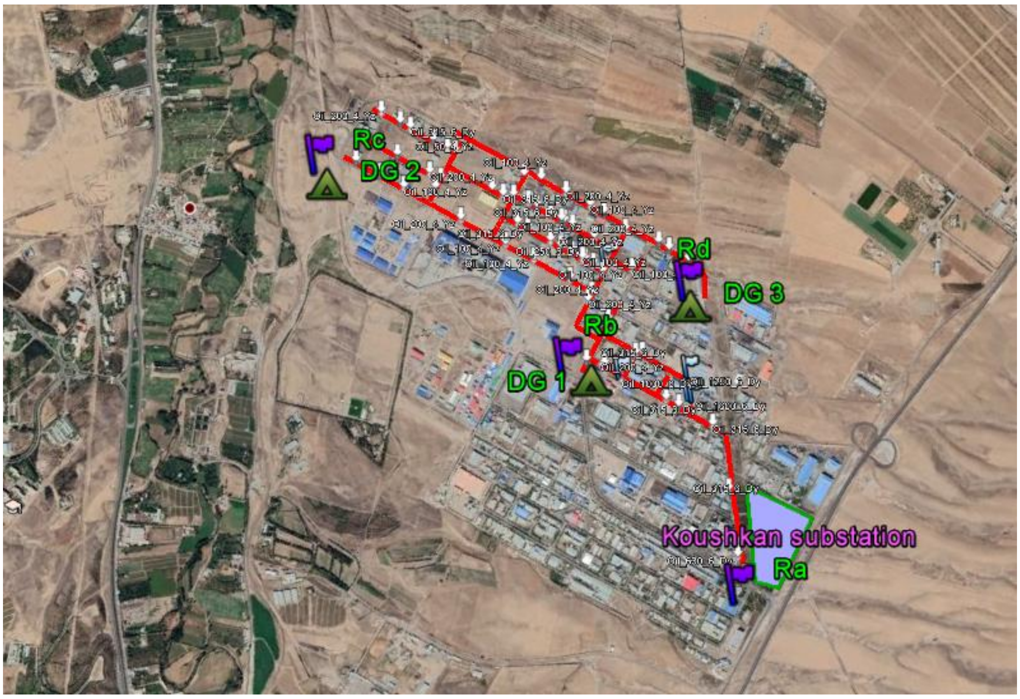
Rc
DG 2
Rd
DG 3
Rb
DG 1
Koushkan substation
Ra

Fig. 4

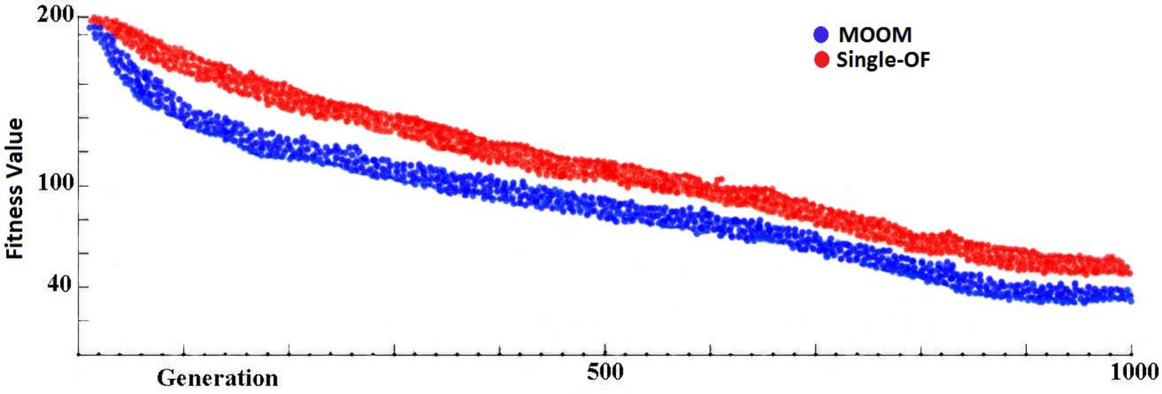
MOOM
Single-OF
Fitness Value
200
100
40
Generation
500
1000

Fig. 5

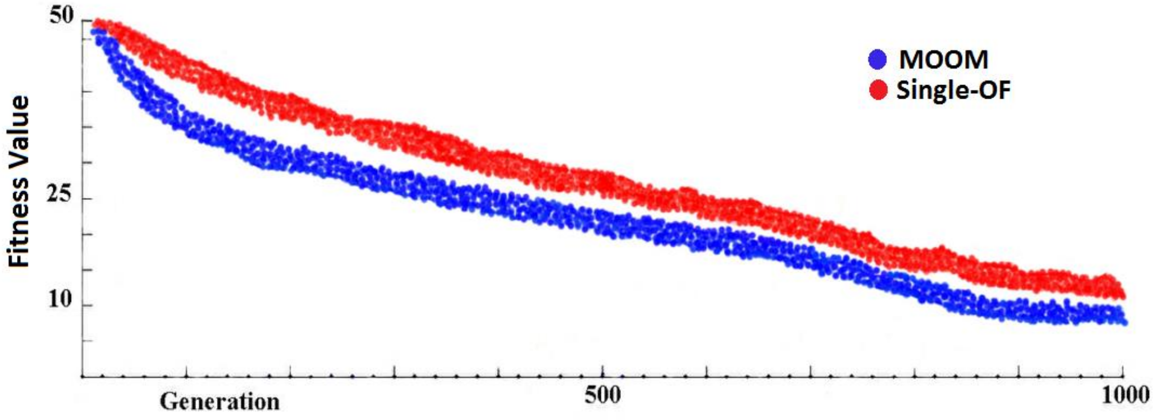

Fig. 6

Table 1

Parameter	Value/Description
Population size	500
Number of generations	1000
Elite counts	5%
Crossover rate	80%
Mutation type	constraint dependent
Selection method	stochastic uniform

Table 2

Parameter	Feature/value	Parameter	Feature/value
Generator type	Gas-engine	Synchronous reactance, X_d	3.498 pu
Rated capacity	1MVA	Transient reactance, $X_d^{'}$	0.2935 pu
Rated voltage	0.4kV	Sub-transient reactance, $X_d^{''}$	0.274 pu
Rated current	1.47kA	Zero-sequence reactance, X_0	0.0419 pu
Frequency	50Hz	Negative-sequence reactance, X_2	0.1531 pu
Nominal Power factor	0.93lag	Rotor type	Round-rotor
Earthling type	Directly grounded	Nominal speed	1200rpm
Power factor range	0.9lag-0.9lead	Winding connection	4-wire Y

Table 3

RELAY	CTR	RELAY	CTR
R1	200:1	**R9**	900:1
R2	200:1	**R10**	900:1
R3	500:1	**R11**	1200:1
R4	500:1	**R12**	1200:1
R5	500:1	**R13**	1000:1
R6	500:1	**R14**	1000:1
R7	1200:1	**R15**	900:1
R8	1200:1	**R16**	900:1

Table 4

Model	**Cascading Outages**
1	Islanding Mode
2	(Substation + DG + Line) Outages
3	(2-case DG) Outages
4	(2-case Line) Outages
5	(Substation + DG) Outages
6	(Substation +Line) Outages
7	(DG + Line) Outages

Table 5

RELAYS	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***
R1	1.5	0.618	1.5	0.584	2.0	0.279	2.5	0.236	1.5	0.541	2.0	0.498	2.5	0.256
R2	0.6	0.512	1.0	0.412	1.5	0.285	2.0	0.251	1.0	0.364	1.5	0.327	1.5	0.274
R3	2.0	0.385	2.0	0.365	1.5	0.373	2.5	0.311	2.0	0.324	2.0	0.315	2.0	0.325
R4	0.8	0.411	1.0	0.412	2.0	0.359	2.0	0.241	1.5	0.402	2.0	0.358	2.0	0.327
R5	1.5	0.395	1.5	0.324	1.0	0.361	2.5	0.215	1.5	0.411	1.0	0.385	1.0	0.314
R6	1.0	0.514	1.5	0.459	2.0	0.325	2.5	0.236	1.5	0.398	2.0	0.345	2.0	0.287
R7	1.5	0.612	2.0	0.541	1.5	0.367	1.5	0.175	1.0	0.511	1.0	0.417	2.0	0.316
R8	1.0	0.495	1.0	0.413	2.0	0.341	2.0	0.169	1.0	0.416	1.5	0.375	0.8	0.319
R9	2.5	0.356	2.5	0.324	2.5	0.252	2.5	0.156	2.5	0.295	2.5	0.256	2.5	0.224
R10	2.0	0.398	1.5	0.369	2.5	0.302	2.5	0.205	0.8	0.324	1.5	0.298	2.5	0.293
R11	1.0	0.664	2.0	0.551	2.0	0.321	1.5	0.213	2.0	0.517	2.0	0.419	2.0	0.267
R12	1.0	0.496	1.5	0.516	2.5	0.413	2.0	0.298	1.5	0.547	2.5	0.568	2.5	0.415
R13	1.0	0.811	2.0	0.801	1.5	0.416	2.0	0.319	1.0	0.753	1.5	0.712	1.5	0.411
R14	1.5	0.514	1.0	0.612	2.5	0.221	2.0	0.116	2.0	0.541	2.5	0.411	1.5	0.275
R15	0.6	0.715	1.5	0.781	1.0	0.351	1.5	0.173	1.0	0.732	1.0	0.685	2.0	0.269
R16	0.8	0.412	1.5	0.252	1.5	0.217	2.0	0.097	1.5	0.311	1.0	0.369	2.5	0.178

Table 6

RELAYS	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6		Model 7	
	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***	I_P	***TMS***
Ra	2.0	0.253	1.5	0.325	2.0	0.197	2.5	0.143	1.5	0.312	2.0	0.297	2.5	0.167
Rb	1.0	0.221	1.0	0.312	1.5	0.156	2.0	0.102	1.5	0.261	1.5	0.243	2.0	0.125
Rc	1.0	0.088	0.5	0.126	1.0	0.081	1.5	0.077	0.5	0.087	0.8	0.084	1.5	0.078
Rd	0.8	0.152	0.5	0.198	1.5	0.124	2.5	0.109	1.0	0.178	1.0	0.174	1.5	0.111

Table 7

	Overall Operation Time						
Network	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
TOSEE feeder	5.554	8.621	3.259	1.518	7.561	6.924	2.332
IEEE 14-BUS	41.567	28.684	16.432	10.695	26.985	23.421	14.845

Table 8

	Number of Mis-coordinations						
Network	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
TOSEE feeder	2	3	2	1	2	2	1
IEEE 14-BUS	7	6	2	1	5	4	2

Table 9

RELAYS	I_P	TMS
R1	2.5	0.234
R2	2	0.279
R3	2.5	0.328
R4	2	0.269
R5	2	0.211
R6	1.5	0.231
R7	1.5	0.165
R8	2	0.168
R9	2.5	0.216
R10	2.5	0.221
R11	1	0.216
R12	2	0.321
R13	2	0.315
R14	2.5	0.115
R15	2	0.189
R16	2	0.116
Sum(t)=11.778 Seconds Number of mis-coordinations=1 α=10.013. Υ_1=112.567, Υ2=108.421		

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