Security-Constrained Optimal Protection Coordination for Dual-Setting Digital Directional Overcurrent Relays in the Distribution Network Including Non-Renewable/Renewable Synchronous Distributed Generation

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Security-Constrained Optimal Protection Coordination for Dual-Setting Digital Directional Overcurrent Relays in the Distribution Network Including Non-Renewable/Renewable Synchronous Distributed Generation

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Abstract: In this paper, the security-constrained optimal protection coordination (SCOPC) is introduced for dual setting digital directional overcurrent relay (DDOCR) in distribution network, which including renewable and non-renewable synchronous distributed generation (SDG). The SCOPC minimizes the total operation time of DDOCRs in primary and backup protection operating to achieve a fast protection coordination. Also, to improve the flexibility in DDOCRs setting, the allowable limits of A and B coefficients, pickup current (PC) and time dial setting (TDS) in both reverse and forward directions are considered as constraints. Another constraint is the Coordination Time interval (CTI). To consideration of the mentioned scheme security, the SCOPC mechanism considered the unavailability of DDOCRs due to their failure, so the stochastic method is used to modelling of this parameter. To calculate the fault current, network variables are proportional to the daily stochastic operation results of distribution network. Moreover, the proposed problem is implemented on the standard distribution networks, and then the optimal solution is obtained with hybrid algorithm of grey wolf optimization (GWO) and training and learning optimization (TLBO). The numerical results illustrate that the proposed algorithm is able to achieve a reliable and fast protection coordination that has a low standard deviation.

Index Terms: Distribution network, Dual setting digital directional overcurrent relay, Relay unavailability, Security-constrained optimal protection coordination, Synchronous distributed generation.

Nomenclature

35

1) Indices and Sets

b, ψ_B	Indices and sets of DDOCRs in backup protection mode
f, ψ_f	Indices and sets of faults
g, ψ_{DG}, ψ_{RES}	Indices and sets of SDGs, sets of renewable SDGs
h, ψ_H	Indices and sets hours
$k(f)$	Fault location for “ f ” faults
n, ψ_N	Indices and sets of buses
r, ψ_R	Indices and sets of DDOCRs
s, ψ_{SC2}	Indices and sets of scenario samples due to uncertainty of load, renewable power, energy price
w, ψ_{SC1}	Indices and sets of DDOCR unavailability uncertainty scenarios

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2) Variables

$A^{fw/p}, A^{rv/b}$	Constant coefficient of DDOCR in forward and reverse discretion
$B^{fw/p}, B^{rv/b}$	Constant coefficient of DDOCR in forward and reverse discretion
I^F	Fault current flow in distribution line in per unit (p.u.)
$IP^{fw/p}, IP^{rv/b}$	Pickup current of DDOCR in forward and reverse discretion
I^{SC}	Fault current flow in DDOCR (p.u.)
OC	Expected operation cost (\$)
OT	Expected total operation time of all DDOCRs (sec)
P^{DG}, Q^{DG}	Active and reactive power of SDG (p.u.)
P^L, Q^L	Active and reactive power of distribution line (p.u.)
P^S, Q^S	Active and reactive power of distribution substation (p.u.)
$TDS^{fw/p}, TDS^{rv/b}$	Time dial setting of DDOCR in forward and reverse discretion (sec)
$t^{fw/p}, t^{rv/b}$	Operation time of DDOCR in forward and reverse discretion (sec)
V, δ	Voltage magnitude (p.u.) and voltage angle (rad)
V^F	The voltage after fault occurrence (p.u.)
μ	Lagrange multipliers

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3) Constants:

A^G	Incidence matrix of SDGs and buses
A^L	Incidence matrix of buses and distribution lines with consideration of current direct
A^{min}, A^{max}	Minimum and maximum amount of A constant in DDOCR
B^L, G^L	Susceptance and conductance of distribution line (p.u)
B^{min}, B^{max}	Minimum and maximum amount of B constant in DDOCR
CTI	Coordination time interval (sec)
IP^{min}, IP^{max}	Upper and lower amount of DDOCR pickup current (p.u.)
P^D, Q^D	Active and reactive load (p.u.)
$\bar{P}^{DG}$	Maximum amount of generation active power of SDG
$\bar{Q}^{DG}, \underline{Q}^{DG}$	Minimum and maximum amount of generation reactive power of SDG (p.u.)
$\bar{S}^L$	Maximum amount of apparent power of distribution line (p.u.)
$\bar{S}^S$	Maximum amount of apparent power of distribution substation (p.u.)
TDS^{min}, TDS^{max}	Minimum and maximum amount of TDS for DDOCR
u	DDOCR unavailability
$\bar{V}, \underline{V}$	Maximum and minimum amount of voltage magnitude (p.u.)
π	Probability of scenario occurrence
λ	Energy price (\$/MWh)
β	Fuel price of non-renewable SDG (\$/MWh)

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41 1. Introduction

42 According to the U.S. Department of Energy, more than 80 percent of power system faults occur in the distribution network
43 ¹. Therefore, the implementation of protection coordination for overcurrent relays will be able to achieve the high and fast
44 protection in the distribution network in the fault occurrence conditions and short circuit current fault ². However, it should be
45 noted that the presence of synchronous distributed generations (SDGs) in the distribution network, along with environmental
46 and distribution system operation benefits, will cause protection issues. So that, the injected short circuit current level of it is
47 high in the fault occurrence conditions, and leads to loss of protection coordination in the network ³. To overcome of this issue,
48 different solutions have been proposed that one of them is the use of a fault current limiter (FCL) besides the SDG ⁴. This method
49 is suitable for the restoration of protection coordination in the radial distribution network, but since the presence of SDG in the
50 network causes a bi-directional power flow, so it is necessary to use of the optimal protection coordination (OPC) scheme ⁵ for
51 digital directional overcurrent relays (DDOCRs) ⁶.

52 So far, many studies have been conducted on the OPC for directional overcurrent relays (DOCRs) in the distribution network
53 ⁷. In ⁸, the OPC scheme is used for DOCRs in the distribution network, which considers the transient stability limitation as a
54 linear constraint. Based on the obtained results in ⁸, it can be seen that the OPC scheme is able to determine the scheduling of
55 DOCRs in such a way that the transient stability limitation is satisfied in the distribution network. In ⁹, the OPC mechanism is
56 applied for DOCRs in meshed distribution network that its optimal solution is achieved with a modified particle swarm
57 optimization (PSO) algorithm. According to the results of this paper, the presence of distributed generations (DGs) causes the
58 loss of optimal coordination of DOCRs, so Ref ⁹ has used FCL with optimal size and location to improve or restore the protection
59 coordination. Also, the proposed scheme in ⁹ is applied for overcurrent relays (OCRs) in a microgrid (MG) based on work of ¹⁰,
60 but in ¹⁰ the directional FCL (DFCL) is used to restore the protection coordination. The effects of changing in network topology
61 and transformer tap on the OPC of DOCRs have also been investigated in ¹¹. Also, the OPC problem of relays in the distribution
62 network with a high penetration of DGs has been presented in ¹², which the sine cosine algorithm is used to achieve the optimal
63 solution. Furthermore, the proposed OPC scheme in ¹² is used in ¹³, which the whale optimization algorithm is applied to achieve
64 the optimal solution. In ¹⁴, DGs transient stability-constrained traditional protection coordination scheme is provided which is
65 not defined as an optimization problem and uses the existing rules on protection coordination, but note that this scheme can be
66 used for small and radial networks. In ¹⁵, the protection coordination problem of MG is introduced with DOCRs in the presence
67 of FCLs, which the combination of cuckoo search algorithm (CSA) and linear programming (LP) is used to solve it. The proposed
68 framework in ¹⁵ is used in ¹⁶ for distribution network concluding superconducting FCLs (SFCLs) and voltage compensators.
69 Finally, Ref ¹⁷ examined the effects of Inverter-based DGs on the protection coordination of DOCRs. Based on the obtained
70 results of it, these types of DGs are able to quickly interrupt their injected fault current into the network, so Inverter-based DGs
71 don't have the same negative effects as SDGs on the protection coordination of distribution network.

72 According to the state of art of this paper, the following research gaps can be extracted:

- 73 • In most studies, pickup current (PC) and time dial setting (TDS) are generally considered as DOCR adjustment parameters
74 ^{18–20}. It is estimated that by adjusting the A and B constants in the digital relays beside the PC and TDS regulations, faster
75 protection coordination can be achieved. In this case, the flexibility of relays setting will be desirable, which has been less
76 studied in other researches.
- 77 • In order to evaluate the high security of the OPC scheme, it is necessary to consider the unavailability of relays that are
78 caused by their failure. However, in most works, this issue has not been considered ^{18–20}, and only the backup relays have
79 been used for the primary relay.
- 80 • It is worth noting that in most paper, the results of power flow are used to calculate the fault current generally, and the level
81 of generation power of SDGs in these conditions is considered constant. However, it should be said that the level of
82 generation power of renewable SDGs, such as wind turbine varies according to the weather conditions. SDGs also operate

at optimal operating conditions. Therefore, it is possible that the calculated fault current by the power flow doesn't obtain a reliable result.

- Most research has used traditional evolutionary algorithms such as genetic algorithm (GA) and PSO algorithm to solve the OPC problem ¹⁹. It is noteworthy that these algorithms are suitable for simple problems. But the OPC problem considering the A, B, PC and TDS for dual setting DDOCRs, will be a complex problem, which is more evident in larger distribution networks. Therefore, it is anticipated that traditional evolutionary algorithms will not be able to provide a reliable optimal solution in this situation.

To overcome the research gaps that mentioned in this paper, the security-constrained optimal protection coordination (SCOPC) scheme for dual setting DDOCRs in the distribution network in the presence of SDGs is expressed. The proposed problem minimizes the total operation time of all DDOCRs in backup and primary protection modes, while it constrained to the allowable limit of relay adjustment parameters and coordination time interval (CTI). In this mechanism, in order to improve the flexibility of relays adjustments and fast protection coordination achievement in case of fault condition, the proposed scheme achieves the optimal value for A, B, PC and TDS parameters in both forward and reverse directions of DDOCRs. In addition, in order to improve and increase the security of the OPC scheme, the unavailability of relays due to their failure is also considered in the proposed scheme. This parameter is behaved as uncertainty, so the stochastic programming is used to model it. In this method, the Monte Carlo simulation (MCS), proportional to the Bernoulli probability distribution function (PDF), obtains the number of scenarios for the unavailability of the relays uncertainty, which is proportional to the forced outage rate (FOR) of the relays. Moreover, the fault current flow of the relays is calculated in commensurate to the optimal daily operation results of the distribution network in the presence of renewable and non-renewable SDGs. This problem minimizes the expected total operation cost of the distribution network and SDGs, which is limited to the AC power flow equations and the SDG constraints. In this problem, the load consumption, energy price and generation power of renewable SDGs are uncertain, and stochastic programming is applied to model these parameters. In this programing, the MCS method first generates a high number of scenarios in proportion to the Normal/Weibull PDF for the consumed load and the energy price / the production power of the renewable SDGs uncertainties. Then, the Kantorovich method is used as a scenario reduction technique to achieve a low number of scenarios with a high probability of occurrence. In the following, the buses voltage and the current flow through the distribution lines are calculated per different fault locations according to the obtained results of the distribution network optimal operation. Finally, to consider the worst case scenario, at all simulation hours and in all scenarios, the fault current flow through the relay is considered to be equal to the maximum value of the fault current passing through the distribution line where the relay is located. It is noteworthy that the two mentioned problems are nonlinear, which in this paper to achieve a optimal solution including low standard deviation in responding, a hybrid optimization algorithm that is combination of the grey wolf optimization (GWO) and teaching-learning-based optimization (TLBO) algorithms is used. Finally, the novelties of proposed mechanism are as follows:

- 114 • Implementation of the SCOPC scheme in the distribution network considering the uncertainty of the unavailability of dual
115 setting DDOCRs
- 116 • Flexibility improvement of dual setting DDOCRs and fast protection coordination achievement by considering the
117 adjustment of A, B, PC and TDS parameters in forward and reverse directions of DDOCRs.
- 118 • Calculate the fault current flow through the relays in proportion to the results of the optimal daily operation of the distribution
119 network.
- 120 • Apply the combined GWO and TLBO algorithm for the proposed problems to obtain an optimal solution containing low
121 standard deviation in responding.

122 The rest of the paper is organized as follows: the SCOPC scheme is described in Section 2. Section 3 presents the problem
123 solution process using a combined GWO and TLBO algorithm. Then the numerical results and conclusion are shown in Sections
124 4 and 5, respectively.

126 2. Proposed protection coordination mechanism

127 In this section, the SCOPC for dual setting DDOCRs in distribution network with SDGs including micro turbines, diesel
128 generators and wind turbine units is presented. In this scheme, the optimal value of the DDOCR adjustment parameters, i.e. $A^{fw/p}$,
129 $A^{rv/b}$, $B^{fw/p}$, $B^{rv/b}$, $IP^{fw/p}$, $IP^{rv/b}$, $TDS^{fw/p}$ and $TDS^{rv/b}$, are calculated in a way that the total operation time of these relays is in two
130 primary and backup protection modes is minimized, while the constraint of the coordination time interval (CTI) is satisfied. One
131 of the ability of the proposed SCOPC in this paper is the unavailability of one of mentioned relays that due to their failure, which
132 will be an innovation aspect of this paper. Therefore, the proposed scheme will be modeled as follows:

$$\min OT = \sum_{w \in \Psi_{SC1}} \pi_w \left(\sum_{f \in \Psi_F} \left(\sum_{r \in \Psi_R} t_{r,f,w}^{fw/p} + \sum_{b \in \Psi_B} t_{r,f,b,w}^{rv/b} \right) \right) \quad (1)$$

Subject to:

$$t_{r,f,w}^{fw/p} = TDS_r^{fw/p} \left(\frac{A_r^{fw/p}}{\left(\frac{I_{r,f}^{SC}}{IP_r^{fw/p}} \right)^{B_r^{fw/p}} - 1} \right) u_{r,w} \quad \forall r, f, w \quad (2)$$

$$t_{r,f,b,w}^{rv/b} = TDS_r^{rv/b} \left(\frac{A_r^{rv/b}}{\left(\frac{I_{r,f,b}^{SC}}{IP_r^{rv/b}} \right)^{B_r^{rv/b}} - 1} \right) u_{r,w} \quad \forall r, f, b, w \quad (3)$$

$$A^{\min} \leq A_r^{fw/p} \leq A^{\max} \quad \forall r \quad (4)$$

$$A^{\min} \leq A_r^{rv/b} \leq A^{\max} \quad \forall r \quad (5)$$

$$B^{\min} \leq B_r^{fw/p} \leq B^{\max} \quad \forall r \quad (6)$$

$$B^{\min} \leq B_r^{rv/b} \leq B^{\max} \quad \forall r \quad (7)$$

$$TDS^{\min} \leq TDS_r^{fw/p} \leq TDS^{\max} \quad \forall r \quad (8)$$

$$TDS^{\min} \leq TDS_r^{rv/b} \leq TDS^{\max} \quad \forall r \quad (9)$$

$$IP_r^{\min} \leq IP_r^{fw/p} \leq IP_r^{\max} \quad \forall r \quad (10)$$

$$IP_r^{\min} \leq IP_r^{rv/b} \leq IP_r^{\max} \quad \forall r \quad (11)$$

$$t_{r,f,b,w}^{rv/b} - t_{r,f,w}^{fw/p} \geq CTI \quad \forall r, f, b, w \quad (12)$$

The proposed SCOPC objective function is shown in Eq. (1), which formulates the minimization of the total operation time of DDOCRs in both primary and backup protection operating considering a number of fault locations. Also, the operation time of each relay in the two forward and reverse directions, which correspond to the primary and backup protection modes can be calculated from the constraints in Eq. (2) and (3), respectively^{3,11}. In constraints (4)-(11), constraints for DDOCRs adjustment variables, i.e. $A^{fw/p}$, $A^{rv/b}$, $B^{fw/p}$, $B^{rv/b}$, $IP^{fw/p}$, $IP^{rv/b}$, $TDS^{fw/p}$ and $TDS^{rv/b}$, are presented, but it should be noted that in most studies, the values of A and B parameters are generally constant for dual setting DOCRs¹⁷. In this paper, in order to flexibility achievement in the settings of the mentioned relays and attain a faster protection coordination, the number of more adjustment parameters are considered for a dual setting DDOCR relay, which is another innovation for this paper. Finally, the constraint of the coordination time interval (CTI) is provided in constraint (12)⁸. According to the constraint in Eq. (12), the minimum operation time of a relay in the backup protection mode than the relay in the primary protection mode should be more than CTI.

In the proposed SCOPC scheme, the unavailability parameter of a DDOCR (u) is used to evaluate the reliability of this scheme. The value of this parameter is equal to zero or one, which is the value of zero/one corresponding to no responding/responding of the DDOCR in the distribution network. This parameter is an uncertainty that follows the Bernoulli PDF and is dependent on the FOR of DDOCR. In addition, MCS is used to generate the scenario for this uncertainty parameter.

In Eqs. (2) and (3), the amount of fault current flow through the relays depends on the value of network variables at the moment before the fault. Generally, in most papers, network variables calculate according to the power flow problem, where the capacity of distributed generations are considered constant^{8,19}. However, it is possible that the variable DGs, such as the wind turbine system are exist in the distribution network, so the level of its production capacity varies according to the weather conditions at different times. Also in distribution network, DGs operate in optimal operation conditions, hence its supplied power level varies at different times. Therefore, it is possible that employment of the results of the power flow calculations lead to error in fault current calculation, so the obtained results of the SCOPC scheme will not be reliable. In this paper, the daily operation

154 problem of distribution network is used to calculate the network variables, which will be another innovation of this paper. Finally,
 155 the operation model of distribution network is formulated as follows:

$$\min OC = \sum_{s \in SC_2} \pi_s \sum_{h \in \Psi_H} \left(\lambda_{h,s} P_{ref,h,s}^S + \sum_{g \in \Psi_{DG}} \beta_g P_{g,h,s}^{DG} \right) \quad (13)$$

Subject to:

$$P_{n,h,s}^S + \sum_{g \in \Psi_{DG}} A_{n,g}^G P_{g,h,s}^{DG} - \sum_{j \in \Psi_N} A_{n,j}^L P_{n,j,h,s}^L = P_{n,h,s}^D \quad \forall n, h, s \quad (14)$$

$$Q_{n,h,s}^S + \sum_{g \in \Psi_{DG}} A_{n,g}^G Q_{g,h,s}^{DG} - \sum_{j \in \Psi_N} A_{n,j}^L Q_{n,j,h,s}^L = Q_{n,h,s}^D \quad \forall n, h, s \quad (15)$$

$$P_{n,j,h,s}^L = G_{n,j}^L (V_{n,h,s})^2 - V_{n,h,s} V_{j,h,s} \left\{ \begin{array}{l} G_{n,j}^L \cos(\delta_{n,h,s} - \delta_{j,h,s}) \\ + B_{n,j}^L \sin(\delta_{n,h,s} - \delta_{j,h,s}) \end{array} \right\} \quad \forall n, j, h, s \quad (16)$$

$$Q_{n,j,h,s}^L = -B_{n,j}^L (V_{n,h,s})^2 + V_{n,h,s} V_{j,h,s} \left\{ \begin{array}{l} B_{n,j}^L \cos(\delta_{n,h,s} - \delta_{j,h,s}) \\ - G_{n,j}^L \sin(\delta_{n,h,s} - \delta_{j,h,s}) \end{array} \right\} \quad \forall n, j, h, s \quad (17)$$

$$\sqrt{(P_{n,j,h,s}^L)^2 + (Q_{n,j,h,s}^L)^2} \leq \bar{S}_{n,j}^L \quad \forall n, j, h, s \quad (18)$$

$$\sqrt{(P_{n,h,s}^S)^2 + (Q_{n,h,s}^S)^2} \leq \bar{S}_n^S \quad \forall n, h, s \quad (19)$$

$$\underline{V} \leq V_{n,h,s} \leq \bar{V} \quad \forall n, h, s \quad (20)$$

$$0 \leq P_{g,h,s}^{DG} \leq \bar{P}_g^{DG} \quad \forall g \in \Psi_{DG} \setminus \Psi_{RES}, h, s \quad (21)$$

$$\underline{Q}_g^{DG} \leq Q_{g,h,s}^{DG} \leq \bar{Q}_g^{DG} \quad \forall g \in \Psi_{DG} \setminus \Psi_{RES}, h, s \quad (22)$$

$$0 \leq P_{g,h,s}^{DG} = \bar{P}_g^{DG} \quad \forall g \in \Psi_{RES}, h, s \quad (23)$$

156 The objective function of the optimal operation problem is presented in Eq. (13), which minimizes the expected total operation
 157 cost of SDGs and the expected received energy cost from the upstream network ¹⁹. Constraints (14)-(17) are correspond to the
 158 power flow equations, which represent the active and reactive power balance in network buses, and active and reactive power
 159 flowing through distribution lines, respectively ^{18,20}. In addition, the technical constraint of the distribution network including
 160 line and substation capacity limits and bus voltage limitations are expressed in Eqs. (18)-(20), respectively ²¹. Constraints (21)
 161 and (22) represent the corresponding equations with the capability curve of the SDG, except for its renewable type such as wind
 162 turbine system, which its generation active and reactive powers limits are presented in Eqs. (21) and (22), respectively ^{22,23}.

Finally, the corresponding constraint with the variable DG is presented in Eq. (23)²³. According to the IEEE1547 standard²⁴, the variable DGs are generally used for energy production and their reactive power control capability is not considered, so following this concept, only the active power constraint of them is considered in this paper.

In Eqs. (13)-(23) of the problem, the load consumption, the energy price and production power of renewable SDG like a wind turbine system are as uncertainty. Therefore, in this paper, stochastic programming is used to model these parameters. In this method, MCS method is used to generate a high number of scenarios corresponding to normal/Weibull PDF for load consumption and energy price/production power of renewable SDG²⁵. Then, the Kantorovich mechanism is used as a scenario reduction method to achieve a low number of scenarios with a high probability of occurrence²⁵.

In this paper, it is assumed that a fault occurs in the distribution line, so to calculate the fault current flow through the DDOCRs corresponding to the fault f , the fault location is selected as a new bus that called k , firstly. Voltage of this node at a time before the fault occurrence is calculated by KVL law. Then, the calculation process of the fault current flow through the DDOCRs is the calculation of the bus voltage after the fault occurrence, which can be calculated by Eq. (24). In this equation, Z is equal to the network matrix admittance with considering bus k , and Z' is equal to the impedance of the fault agent. By calculating the bus voltages, the current flow through the distribution line after the fault occurrence is calculated according to Ohm's law as in Eq. (25). Finally, to extract a reliable OPC and the worst-case scenario, which corresponds to the maximum current flow through the DDOCRs, must be considered. Therefore, in this paper, as in Eq. (26), the fault current flow through a relay is equal to the maximum fault current flow through the distribution line in which the relay is located considering all simulation hours and all scenarios.

$$V_{n,h,s,f}^F = V_{n,h,s} - \frac{Z_{n,k(f)}}{Z_{k(f),k(f)} + Z_f} V_{k(f),h,s} \quad \forall n, h, s, f \quad (24)$$

$$I_{n,j,h,s,f}^F = \left| \frac{V_{n,h,s,f}^F - V_{j,h,s,f}^F}{Z_{n,j}^L} \right| \quad \forall n, j, h, s, f \quad (25)$$

$$I_{r,f}^{SC}, I_{r,f,b}^{SC} = \max(I_{n,j,h,s,f}^F) \quad \forall r(n, j), f \quad (26)$$

3. Solution method

The OPC problem will be complex one due to the employment of a number of high adjustment variables for dual setting DDOCR, especially in larger distribution networks. Also, the optimal operation problem of distribution network has such conditions. Therefore, it is predicted that the employment of an evolutionary algorithm will not be able to achieve a reliable response. To overcome for this issue, this paper uses a combination of meta-heuristic algorithms such as combination of GWO²⁶ and TLBO²⁷ to solve the proposed problems. It is noteworthy that in this case, the number of updating steps of the decision variables value is more than employment an evolutionary algorithm, so it is possible to obtain an optimal solution considering

low standard deviation with less computational complexity. Another advantage of this algorithm is the lack of adjustment parameters in this algorithm ^{26,27}.

In the proposed solution method for SCOPC, to consider the constraint in Eq. (12), this term is added as a penalty function like $\sum_{r,f,b,w} \mu_{r,f,b,w} \max\left(0, CTI - \left(t_{r,f,b,w}^{rv/b} - t_{r,f,w}^{fw/p}\right)\right)$ to the objective function in Eq. (1), which $\mu \geq 0$ represents the penalty variable or Lagrange multiplier ². Therefore, to solve the new problem based on the Eqs. (27)-(29), the initial population is randomly obtained for decision variables, i.e. $A^{fw/p}, A^{rv/b}, B^{fw/p}, B^{rv/b}, IP^{fw/p}, IP^{rv/b}, TDS^{fw/p}, TDS^{rv/b}$ and μ corresponding to constraints in Eqs. (4)-(11) and (29), firstly. Then, the fitness function in Eq. (27) and operating time of DDOCRs in (2) and (3), is calculated for the resulting population. The optimal point for the initial condition corresponds to the minimum point for the fitness function. In the next steps, the decision variables are executed. Therefore, first the updating steps of the TLBO algorithm, i.e. the teacher phase and then the student phase, are implemented. In the third phase, the updating process of GWO is presented. These steps continue until the convergence point is reached, in which it is assumed that the convergence point is available after maximum iteration with the abbreviation $iter_{max}$.

$$\begin{aligned} \min F_1 = & \sum_{w \in \Psi_{SC1}} \pi_w \left(\sum_{f \in \Psi_F} \left(\sum_{r \in \Psi_R} t_{r,f,w}^{fw/p} + \sum_{b \in \Psi_B} t_{r,f,b,w}^{rv/b} \right) \right) \\ & + \sum_{r,f,b,w} \mu_{r,f,b,w} \max\left(0, CTI - \left(t_{r,f,b,w}^{rv/b} - t_{r,f,w}^{fw/p}\right)\right) \end{aligned} \quad (27)$$

Subject to:

$$\text{Constraints (2)-(11)} \quad (28)$$

$$\mu \geq 0 \quad (29)$$

The solving process of optimal operation problem of distribution network is the same as the solving process of SCOPC problem. Therefore, the technical constraints of the network, (18)-(20), are added as a penalty function to the objective function in Eq. (13), which is a new problem that provided in Eqs. (30)-(32). First, a random initial population for the decision variables P^{DG}, Q^{DG} , and μ is calculated based on constraints in Eqs. (21)-(23) and (32). Then the value of network variables are calculated with the AC power flow equations that given in Eqs (16)-(17). Also, these equation is solved based on the backward-forward power flow method ²⁸. Finally, the fitness function will be evaluated using the Eq. (30) for the whole population of decision variables. The minimum point is optimal response. In the following, the updating steps will be implemented as the SCOPC problem solving process until the convergence point is reached. Finally, the flowchart of proposed algorithm is shown in Fig. 1.

$$\begin{aligned}
\min \quad F_2 = & \sum_{s \in SC_2} \pi_s \sum_{h \in \Psi_H} \left(\lambda_{h,s} P_{ref,h,s}^S + \sum_{g \in \Psi_{DG}} \beta_g P_{g,h,s}^{DG} \right) + \\
& \sum_{n,h,s} \bar{\mu}_{n,h,s}^V \max(0, V_{n,h,s} - \bar{V}) + \underline{\mu}_{n,h,s}^V \max(0, \underline{V} - V_{n,h,s}) \\
& + \sum_{n,h,s} \bar{\mu}_{n,h,s}^S \max\left(0, \sqrt{(P_{n,h,s}^S)^2 + (Q_{n,h,s}^S)^2} - \bar{S}_n\right) + \\
& \sum_{n,h,s} \bar{\mu}_{n,j,h,s}^L \max\left(0, \sqrt{(P_{n,j,h,s}^L)^2 + (Q_{n,j,h,s}^L)^2} - \bar{S}_{n,j}\right)
\end{aligned} \tag{30}$$

Subject to:

$$\text{Constraints (14)-(23)} \tag{31}$$

$$\mu \geq 0 \tag{32}$$

Fig. 1 Flowchart of proposed solution algorithm

4. Numerical results

In this section, the proposed problem is simulated on a standard 33-bus and 119-bus distribution networks²⁹ in the MATLAB software environment. Note that the MCS method in the SCOPC scheme generates 30 scenarios for the uncertainty of the DDOCRs unavailability, which is assumed the FOR of relays is equal to 0.5%. But it produces 1000 scenarios for the uncertainty of load consumption, energy prices, and production power of renewable SDGs, assuming a standard deviation of 10% in the distribution network operation problem. Then, in this problem, the Kantorovich method selects 30 scenarios from the generated scenarios, which have a high probability of occurrence. In addition, for the proposed combined GWO and TLBO algorithm, the

population and the maximum of coverage iteration are selected equal to 50 and 3000, respectively.

4.1 Case Studies

A) *IEEE 33-bus radial distribution system*: Single Line diagram of IEEE 33-bus radial distribution system with 12.66 kV base voltage and 1 MVA base power is plotted in Fig. 2²⁹. The characteristic of lines and distribution substation are provided in²⁹. The allowable voltage limits is equal [0.9 p.u., 1.05 p.u.]. Also, the load profile and the daily energy price curve are presented in³⁰. It is noteworthy that in terms of network load, time interval 1:00 to 7:00 is equal to the low load case, which has an energy price of 16 \$/MWh. Also, the time interval 17:00 to 22:00 is correspond to the peak load case which the energy price is 30\$/MWh. Other time intervals are correspond to middle load case and its energy price is 24 \$/MWh. The network also has three non-renewable SDGs with a capacity of 500 kVA and a fuel price of 20 \$/MWh on the busses 14, 27 and 32, whose them DDOCRs are marked with numbers 35, 37 and 38, respectively. Two renewable SDGs (wind turbine) with 400 kW capacity are installed in busses 6 and 20, which DDOCRs 34 and 36 are located in these buses, respectively. The daily wind power rate curve is also presented in³⁰. In addition, the left/hand relays of bus n are considered as R_n/R_n' . It is assumed that the fault location is in the center of the distribution lines, which its details are presented in Table 1. In this table, the operation modes of different DDOCRs for different fault locations are provided. Based on², relays in both sides (left and right) of each fault location act as the primary mode. An example of how to determine the backup relays is given. It is assumed that a fault has occurred in the distribution line between buses 13 and 14. In this case, R_{13}' and R_{14} in direction of fw/p are in the primary protection mode. For the R_{13}' in direction fw/p, the R_{13} in direction rv/b are in the backup protection mode and for the R_{14} in direction fw/p, the R_{14}' and R_{35} in direction rv/b will be in the backup mode.

In the SCOPC scheme, the minimum and maximum values for A is equal to 0.14 and 13.5, respectively. These values for B are equal to 0.02 and 1, respectively. For TDS, they are equal to 0.1 and 1 sec. The CTI is considered equal to 0.3 sec. The minimum and maximum values of PC for a relay (in the distribution line or in the SDG path) are equal to 100% and 130% current of the distribution line or SDG in the pre-fault occurrence, respectively.

B) *IEEE 119-bus radial distribution system*: The single line diagram of the IEEE 119-bus radius distribution network is shown in Fig. 3, which its distribution lines and load peak characteristics are provided in²⁹. The daily load factor curve is also expressed in³⁰. This network also has 400 kVA non-renewable SDGs with 20 \$/MWh fuel price that installed on busses 24, 39, 48, 73, 94 and 109, whose them DDOCRs are marked with numbers 120-125, respectively. Also, the 400 kW renewable SDGs with 126 to 129 relays are connected to buses 4, 30, 65 and 101. As the IEEE 33-bus distribution network, it is assumed that at the center of each distribution line there is a possibility of fault occurrence. The process of determining the primary and backup protection mode for relays appropriate to different fault locations such as Table 1. Finally, other problem data such as energy prices, the allowable limits of DDOCR and CTI adjustment parameters are the same as the IEEE 33-bus distribution network.

Fig. 2 Single line diagram of IEEE 33-buses distribution network ²⁹

Table 1: Operation modes of DDOCRs for different fault location

Fault	Fault location (between busses)	P ₁	B	P ₂	B
34	1-2	R1'fw/p	R1rv/b	R2fw/p	R2'rv/b, R2''rv/b
35	2-3	R2'fw/p	R2rv/b	R3fw/p	R3'rv/b, R3''rv/b
36	3-4	R3'fw/p	R3rv/b	R4fw/p	R4'rv/b
37	4-5	R4'fw/p	R4rv/b	R5fw/p	R5'rv/b
38	5-6	R5'fw/p	R5rv/b	R6fw/p	R6'rv/b, R6''rv/b, R34rv/b
39	6-7	R6'fw/p	R6rv/b, R34rv/b	R7fw/p	R7'rv/b
40	7-8	R7'fw/p	R7rv/b	R8fw/p	R8'rv/b
41	8-9	R8'fw/p	R8rv/b	R9fw/p	R9'rv/b
42	9-10	R9'fw/p	R9rv/b	R10fw/p	R10'rv/b
43	10-11	R10'fw/p	R10rv/b	R11fw/p	R11'rv/b
44	11-12	R11'fw/p	R11rv/b	R12fw/p	R12'rv/b
45	12-13	R12'fw/p	R12rv/b	R13fw/p	R13'rv/b
46	13-14	R13'fw/p	R13rv/b	R14fw/p	R14'rv/b, R35rv/b
47	14-15	R14'fw/p	R14rv/b, R35rv/b	R15fw/p	R15'rv/b
48	15-16	R15'fw/p	R15rv/b	R16fw/p	R16'rv/b
49	16-17	R16'fw/p	R16rv/b	R17fw/p	R17'rv/b
50	17-18	R17'fw/p	R17rv/b	R18fw/p	-
51	2-19	R2''fw/p	R2rv/b	R19fw/p	R19'rv/b
52	19-20	R19'fw/p	R19rv/b	R20fw/p	R20'rv/b, R36rv/b
53	20-21	R20'fw/p	R20rv/b, R36rv/b	R21fw/p	R21'rv/b
54	21-22	R21'fw/p	R21rv/b	R22fw/p	-
55	3-23	R3''fw/p	R3rv/b	R23fw/p	R23'rv/b
56	23-24	R23'fw/p	R23rv/b	R24fw/p	R24'rv/b
57	24-25	R24'fw/p	R24rv/b	R25fw/p	-
58	6-26	R6''fw/p	R6rv/b	R26fw/p	R26'rv/b
59	26-27	R26'fw/p	R26rv/b	R27fw/p	R27'rv/b, R37rv/b
60	27-28	R27'fw/p	R27rv/b, R37rv/b	R28fw/p	R28'rv/b
61	28-29	R28'fw/p	R28rv/b	R29fw/p	R29'rv/b
62	29-30	R29'fw/p	R29rv/b	R30fw/p	R30'rv/b
63	30-31	R30'fw/p	R30rv/b	R31fw/p	R31'rv/b
64	31-32	R31'fw/p	R31rv/b	R32fw/p	R32'rv/b, R38rv/b
65	32-33	R32'fw/p	R32rv/b, R38rv/b	R33fw/p	-

R2'': DDOCR in left side of line 2-19, R3'': DDOCR in left side of line 3-23, R6''= DDOCR in left side of line 6-25

Fig. 3 Single line diagram of IEEE 119-buses distribution network ²⁹

4.2 Results

In this section, the capabilities of the proposed scheme on the IEEE 33-bus and 119-bus distribution networks are evaluated, which the numerical results obtained by coding the proposed problem in MATLAB software.

A) *Investigating the potential of the proposed solution algorithm*: The statistical results of the obtained optimal response from different solvers such as sine cosine algorithm (SCA) ¹², krill herd optimization (KHO) algorithm ³¹, GWO ²⁶, TLBO ²⁷ and combination of GWO and TLBO are provided in Table 2. It is noteworthy that for all proposed algorithms, the population size is 50 and the maximum of convergence iteration is 3000, and regulation parameters for SCA and KHO solver are presented in ¹² and ³¹, respectively. Also, to achieve the statistical results such as the mean of the final optimal response and its standard deviation, each proposed algorithm is repeated 20 times. Based on the results that presented in Table 2, it can be seen that the

proposed algorithm (combination of GWO and TLBO) for the objective functions in Eqs. (1) and (13) based on 33-bus network data has been able to coverage at the 731 and 1273 iterations with 12.7 and 82.1 computational time, respectively. These values for the 119-bus network are at the 1046 and 1836 iterations with 21.2 and 103.5 computational times, respectively. Comparing these results with the obtained convergence iteration and computational time for other proposed algorithms indicates that the combined algorithm GWO and TLBO can be reached to minimum value of objective function (OT and OC) in the shortest time and lowest iteration compared to SCA, KHO, GWO and TLBO. In addition, the obtained mean value of OT (OC) with combination of GWO and TLBO are equal to 52.32 sec (902.73 \$) and 123.62 sec (2853.15 \$) in the SCOPC (network optimal operation) scheme of the 33-bus and 119-bus distribution networks, respectively, which in comparison to other algorithms that described in this section are the lowest. This also indicates the ability of the proposed algorithm to achieve the lowest optimal point compared to other algorithms. Finally, based on rows of 7 and 16 in Table 2, it can be seen that the standard deviation of the objective functions of OT and OC for the combination of GWO and TLBO algorithm is much lower than for other algorithms. Also, the standard deviation values of these objective functions in the two 33-bus and 119-bus distribution networks are very close to each other, but this is not established in the other algorithms that presented in Table 2. Hence, it can be said that the proposed algorithm is able to achieve the best solution including low standard deviation, which is very little dependent on the problem data. But in SCA, KHO, GWO and TLBO solvers, increasing the scale of problem data (comparing the results of the 119-bus network to the 33-bus network) increases the standard deviation of the optimal point, so it is predicted that in large real networks, these algorithms don't have the ability to achieve the reliable optimal solution. However, since the combination of GWO and TLBO has the same and low standard deviation values in the two mentioned networks, the consistency of this algorithm is slightly dependent on the data scale of the problem and is suitable for large scale networks. It is noteworthy that all the benefits provided in this section confirm the fourth innovation in Section 1.

Table 2: Statistical analysis results of different algorithms

33-bus distribution network										
Problem	SCOPC					Distribution network operation				
Algorithm	SCA	KHO	GWO	TLBO	GWO+TLBO*	SCA	KHO	GWO	TLBO	GWO+TLBO*
Convergence iteration	1294	1472	956	937	731	1783	1836	1503	1421	1273
Calculation time (s) at convergence iteration	29.5	32.2	18.1	18.6	12.7	127.4	136.8	94.1	93.2	82.1
Mean value of objective function	66.35	64.94	58.21	56.33	52.32 (s)	978.67	971.11	953.27	945.16	902.73 (\$)
Standard deviation (%) for objective function	4.04	3.59	2.12	1.92	0.97	4.24	4.18	2.57	2.31	1.02
119-bus distribution network										
Problem	SCOPC					Distribution network operation				
Algorithm	SCA	KHO	GWO	TLBO	GWO+TLBO*	SCA	KHO	GWO	TLBO	GWO+TLBO*
Convergence iteration	1711	1906	1409	1312	1046	2577	2737	2208	2111	1836
Calculation time (s) at convergence iteration	51.7	60.22	32.43	29.8	21.2	194.72	241.44	150.61	147.27	103.5
Mean value of objective function	171.81	163.55	145.37	141.23	123.62 (s)	3583.26	3485.19	3121.59	3064.23	2853.15 (\$)
Standard deviation for objective function	5.89	5.34	3.87	3.12	0.99	6.94	6.11	4.22	3.99	1.05

B) *Investigation of network operation situation:* In this section, the results of optimal operation of the 33-bus and 119-bus

distribution networks in the presence of non-renewable and renewable SDGs (wind system type) are provided. Fig. 4 shows the expected daily curve of SDGs active power. Based on Fig. 4(a), it can be seen that the active power of the wind turbine system has different values for different hours, which is due to changes in wind speed during the day and night. Also, according to Fig. 4(b), the non-renewable SDGs in the two mentioned networks are off for 1:00 to 7:00 and don't inject the active power into the network. Because based on the data in section 4-1, at these hours the purchased energy price from the upstream network is equal to 16 \$/MWh, while the fuel price of non-renewable SDGs is equal to 20 \$/MWh. Therefore, in order to minimize the expected operation cost (OC), the most optimal status is for consumers to be fed by the upstream network. But in other hours, the opposite is true, so these SDGs inject their maximum active power into the network. In addition, Table 3 presented the advantages of the proposed optimal operation in proportion to the optimal scheduling for SDGs as illustrated in Fig. 4. Based on this, it can be seen that the operation cost of the IEEE 33-bus distribution network, regardless of the presence of SDGs is equal to 1950 \$, the energy losses equal to 1.878 p.u., and the maximum voltage drop equal to 0.087 p.u., However, these operating indices, if SDGs are present are reduced to 902.73\$, 0.8988 p.u and 0.0437 p.u., respectively, but the maximum overvoltage is created to 0.0115 p.u., which is much less than its allowable limit i.e. 0.05 p.u. (1.05-1). Therefore, these conditions indicate the improvement of the mentioned indicators by about 53.7% $((1950-902.73)/1950)$, 51.1% $((1.878-0.8988)/1.878)$ and 49.8% $((0.087-0.0437)/0.087)$, respectively. This situation is also established for IEEE 119-buses distribution network, so that the expected operation costs, energy losses and maximum voltage drop in the presence of SDGs in the network compared to the mentioned distribution network without the presence of SDGs are reduced by about 38%, 47.8 % and 43.2%, respectively.

As said in Section 1, researches generally uses the power flow analysis results of distribution network with considering constant injection active power of SDGs to calculate the fault current flow through the relays. The OPC (it is not consider security situation) scheme is considered appropriate under case I. In other words, it is assumed that the injected active power of all SDGs is equal to their maximum capacity, and other data is proportional to the peak hours. The OPC scheme is also evaluated based on the results of the optimal operation of the distribution network in the case II. The results of this section are presented in Table 4. According to this table, the total operation time of all DDOCRs in the two primary and backup protection modes considering all the fault locations that provided in Table 1 for case I in the two 33-bus and 119-bus networks are 55.83 sec and 135.95 sec, respectively. These total operation times for case II are 49.12 sec and 120.41 sec, respectively. Therefore, the computational difference between the methods that presented in cases I and II for the two networks is about 13%. However, since the optimal operation scheme considers the voltage changes of different buses in proportion to the changes in the power level of SDGs and loads, so case II achieves more accurate results for calculating the fault current. From this, it can be said that the OPC results obtained in the case II are more reliable than the case I, which confirms the third innovation in Section 1.

(a)

(b)

Fig. 4 Expected active power daily curve, a) renewable SDGs, b) non-renewable SDGs

Table 3: Expected operation indices values

33-bus distribution network			
Case	Operation cost (\$)	Energy loss (p.u)	Maximum value of overvoltage/voltage drop (p.u)
Power flow analysis	1950	1.878	0/0.087
Optimal operation	902.73	0.8988	0.0115/0.0437
119-bus distribution network			
Case	Operation cost (\$)	Energy loss (p.u)	Maximum value of overvoltage/voltage drop (p.u)
Power flow analysis	4525.5	3.672	0/0.092
Optimal operation	2853.15	1.917	0.0143/0.0523

Table 4: OPC results based on optimal operation and power flow of distribution system in presence of SDGs

Network	Case	Total operation time of all DDOCR (s)	Deviation (%)
33-bus	I	55.83	$(55.83 - 49.12)/49.12 = 13.66\%$
	II	49.12	
119-bus	I	135.95	$(129.95 - 120.41)/120.41 = 12.9\%$
	II	120.41	

C) *Proposed SCOPC scheme capabilities*: In this section, five case studies are presented to evaluate the proposed SCOPC scheme capabilities. The details of them are as follows:

- **Case I:** Investigation of the OPC for overcurrent relays (OCRs) considering the constant value of the pickup current, which is provided in traditional OPCs. So that the OCR pickup current is generally equal to 120% of the current flow through the OCR before the fault occurrence, and the values of A and B are equal to 0.14 and 0.02, respectively.
- **Case II:** investigation of the OPC for OCRs that the values of A and B are equal to 0.14 and 0.02.
- **Case III:** investigation of the OPC for DOCRs that the values of A and B are equal to 0.14 and 0.02.
- **Case IV:** investigation of the OPC for DDCORs
- **Case V:** investigation of the SCOPC for DDCORs

The results of this section are shown in Table 5 for the two 33-bus and 119-bus distribution networks. As can be seen from this table, the OPC scheme for DDOCR in case IV with 8 parameters, i.e. $A^{fw/p}$, $A^{rv/b}$, $B^{fw/p}$, $B^{rv/b}$, $IP^{fw/p}$, $IP^{rv/b}$, $TDS^{fw/p}$ and $TDS^{rv/b}$, is able to achieve faster protection coordination than other case studies, which confirms the second innovation in Section 1. It is noteworthy that this advantage is obtained in such a way that $A^{fw/p}$ and $B^{fw/p}$ are set to values greater than 0.14 and 0.02, and $A^{rv/b}$ and $B^{rv/b}$ are around values of 0.14 and 0.02. $TDS^{fw/p}$ is set to its smallest value i.e. 0.1 second, but $TDS^{rv/b}$ is set to a higher value than $TDS^{rv/b}$ in cases I to III. In the following, the pickup current of DDOCRs in the case IV is less than that of the pickup current in cases I to III. Finally, the OT value for the SCOPC scheme in the case V for the two 33-bus and 119-bus networks are 52.32 sec and 123.62 sec, respectively. This fitness function are equal to 49.12 sec and 120.61 sec for the case IV, respectively. This time difference is due to the uncertainty of the unavailability of DDOCRs, which has a more reliable response confirming the first innovation capability in section 1.

Table 5: Results of different OPC or SCOPC schemes

Network	Case	OT (sec)	Mean value of							
			$A^{fw/p}$	$A^{rv/b}$	$B^{fw/p}$	$B^{rv/b}$	$TDS^{fw/p}$	$TDS^{rv/b}$	$IP^{fw/p}$	$IP^{rv/b}$
33-bus	I	63.38	0.14	0.14	0.02	0.02	0.1824	0.1824	0.8643	0.8643
	II	59.84	0.14	0.14	0.02	0.02	0.1781	0.1781	0.8229	0.8229
	III	53.63	0.14	0.14	0.02	0.02	0.1000	0.2361	0.8177	0.8175
	IV	49.12	1.1263	0.1463	0.3317	0.0291	0.1000	0.2521	0.8038	0.8035
	V	52.32	1.1271	0.1468	0.3345	0.0299	0.1000	0.2578	0.8072	0.8070
119-bus	I	138.64	0.14	0.14	0.02	0.02	0.1611	0.1611	0.7245	0.7245
	II	133.49	0.14	0.14	0.02	0.02	0.1592	0.1592	0.6922	0.6922
	III	125.11	0.14	0.14	0.02	0.02	0.1000	0.2018	0.6891	0.6889
	IV	120.41	1.1936	0.1458	0.3119	0.0284	0.1000	0.2374	0.6785	0.6783
	V	123.62	1.1971	0.1465	0.3134	0.0293	0.1000	0.2403	0.6791	0.6788

5. Conclusions

In this paper, SCOPC scheme for coordination protection of dual setting DDOCRs in distribution network with renewable and non-renewable SDGs is presented. The SCOPC scheme minimizes the expected total operation time of these relays in the two primary and backup protection modes considering several fault locations, which is constrained to the allowable limits of DDOCR adjustment parameters and CTI limitations. In this problem, the unavailability of DDOCRs is uncertain, and stochastic

programming is used to model it. In addition, this paper calculates the fault current flow through the relay corresponding to the stochastic operation results of the distribution network, which minimizes the expected total operation cost of network and non-renewable SDGs, while constrained the equations of the optimal AC power flow in the distribution network. Also in this problem, stochastic programming is applied to model the uncertainties of load consumption, energy price and production power of renewable SDGs. Finally, the optimal solution for both optimal operation and SCOPC problems is achieved by a combined GWO and TLBO algorithms. Based on the obtained numerical results in this paper, it was seen that the proposed solver is able to obtain the most optimal point in lower coverage iteration and computational time with low standard deviation in responding to other SCA, KHO, GWO and TLBO algorithms. Also, the standard deviation of this algorithm has a low dependence on the data scale of the problem, so that for two networks and two problems (SCOPC and optimal operation) is about 1%. In addition, based on the simulation results, it was illustrated that the SCOPC scheme based on optimal operation results is about 13% more accurate than the SCOPC based on the power flow analysis considering the constant value for the active power of SDGs. Finally, the protection coordination of DDOCRs has a faster operation time due to the flexibility in different adjustment parameters than OCRs and DOCRs. Also, due to considering the unavailability of DDOCRs in the SCOPC scheme, the obtained results in this scheme have better reliability and confidence than the OPC scheme.

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Author Contributions

All authors participated in the discussion and wrote the manuscript.

Competing interests

The authors declare no conflict of interest.

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Figures

Figure 1

Flowchart of proposed solution algorithm

Figure 2

Single line diagram of IEEE 33-buses distribution network 29

Figure 3

Single line diagram of IEEE 119-buses distribution network 29

(a)

(b)

Figure 4

Expected active power daily curve, a) renewable SDGs, b) non-renewable SDGs