Improving Coordination and Operating Speed of Overcurrent Relay against Contingency of Presence of Distributed Generators

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Received: 2019-11-29
Accepted: 2020-09-16

Abstract
The presence or absence of distributed generation (DG) sources in a distribution network has a probabilistic nature. In the event of connection or disconnection of these sources, the fault current through a relay and the relay operating time are affected, which leads to miscoordination. For solving this issue, coordination constraints corresponding to the presence or absence of DGs have to be considered in the overcurrent relay coordination problem (CP). The incorporation of these constraints increases the operating time (OT) of the conventional overcurrent relays (OCRs). In this paper, a novel adaptive characteristic is proposed to solve this unwanted effect. Accordingly, a function proportional to the equivalent impedance (EI) seen by the relay is added to the relay characteristic. This EI is calculated via in-situ measurement of voltage and current before the occurrence of a fault, continuously; when the fault occurs, the calculated impedance is used in the relay characteristic to determine the OT. The addition of this function to the conventional overcurrent relay characteristic, reduces the effects of disconnecting the DGs on the coordination constraint, and in general, improves the OT of the relay. Based on the analytical relations and simulation results, it is shown that the OTs of the primary and backup relays with the proposed characteristic are improved compared to the relays with the conventional characteristic.

Keywords
Adaptive Characteristic, Contingency, Coordination, Distributed Generator (DG), Equivalent Impedance (EI), Overcurrent relay (OCR).

1. Introduction

The duty of a protection system is to identify the fault quickly and to eliminate the fault by isolating the smallest part of the network. The conventional protection devices in distribution systems are overcurrent relays (OCRs).

Overcurrent relays have various time-current characteristics, such as instantaneous and inverse time or the combination of them. In instantaneous characteristic, the relay trips once the current flow exceeds the current setting, while in inverse time characteristic, the operating time (OT) of the relay has an inverse relation with the relay current. Accordingly, the OT decreases with an increase in current amplitude [1]. Inverse time characteristic is more used because of its advantages (e.g., higher operation speed of the protection system, better overlap of protection zones, etc.) [2]. For coordinating the relays with inverse time characteristic, a minimum coordination time interval (CTI) is needed between the operation of the backup and primary relays [3].

Today, distributed generation (DG) sources have been being developed in distribution systems due to their numerous advantages, such as voltage regulation, power loss reduction, lower environmental pollution, power quality improvement, higher reliability, reactive power injection and so on [4-6]. Despite many benefits of using DG units, there are some major technical challenges for controlling and protecting distribution systems [7 ‹8].

Connecting multiple resources at different points of the distribution system leads to some changes in fault current over the lines compared to conventional radial systems [9 ‹10]. The performance of OCRs can be affected by the variations in the short circuit level of the lines, which may result in miscoordination between relay pairs [11 ‹12]. Another factor that intensifies the effects of DGs on the coordination of OCRs is the stochastic nature of these resources [13]. According to the technical and geographical conditions, the output power and even the connection of wind and solar farms have a stochastic nature [14-16].

Proposed methods for improving the performance of overcurrent relays in the presence of DG sources are divided into local and global methods. The overcurrent relays that operate based on the local methods use only the information at the relay location (voltage and current measured at the relay location). However, in global methods, pieces of information from other parts of the network or other relays are sent to the corresponding relay or the central unit.

In [17], the coordination retrieval of OCRs is discussed in the event of a change in the structure of the system due to connection/disconnection of DG sources. In this method, a communication system is used to detect the change in the structure and relay adaptation.

In [18 ،19], a bi-directional characteristic (forward and reverse) is proposed to increase the operation speed of OCRs in the presence of DGs. The forward characteristic is intended for the faults in the forward direction of the relay and the reverse characteristic for the faults behind (backup protection). In this situation, there is no need to coordinate the forward and reverse characteristics. However, the most important problem is the lack of coordination among the operations of the relays based on their forward characteristic [20]. The suggested solution in [21] is the use of communication links to block the operation of the relays downstream to the main relay, in accordance with method of [22].

In [23], the status of circuit breakers (CBs) and resources (DG) all over the network is transmitted to relays, and their settings are updated according to the latest changes. The main disadvantage of this method is its dependence on communication systems, which results in higher cost and lower reliability.

In [24], network information is transmitted to the central processing unit via communication links, and using a hybrid algorithm of fuzzy and genetic methods, the relay settings are updated. In [25], an adaptive approach is presented based on monitoring the entire network information by the central processing unit and updating relay settings.

In [26], various settings of overcurrent relays operation for different cases of the presence of DG units are calculated and stored in the relays. Using communication links and the K-means classification method, the appropriate settings are selected for the relays. The major drawbacks of these methods are the lack of the required communication infrastructures, low reliability and high cost.

In the following, some local methods are discussed. In the method proposed in [14], to maintain the overcurrent protection coordination (reclosers and fuses), the output current of DG electronic converters is controlled to be within the allowable range. The most important drawback of this method is its applicability to only inverter-based DGs.

In [27], the maximum allowable capacity of DGs is determined with the purpose of maintaining the coordination. This approach imposes some technical and economic limitations on the operation of DGs. In [28 ، 29], installation of fault current limiters (FCLs) bounds the fault current amplitude within a certain range. Making use of FCLs, not only does not solve the problem of CTI reduction due to the disconnection of DG, but also has a high implementation cost.

In [30 ،31], a new time-current-voltage characteristic is proposed for the operation of OCRs in the presence of DGs. In the event of a fault in a location closer to the relay, there is a more significant voltage drop. The same feature is used to maintain the coordination of the relay pairs in the presence of DGs. Although the improvement in the operation speed of the relays is the result of this characteristic, the contingency of the disconnection of DGs is not addressed in this reference. Additionally, the performance of the proposed method is evaluated in the presence of only synchronous DGs.

In [32], the connection of DGs is also considered as one of the several contingencies influencing the coordination of OCRs. The proposed strategy is to consider coordination constraints in the presence of DGs. However, this leads to an increase in the OT of the conventional OCRs.

In this paper, the optimal settings of OCRs with coordination constraints corresponding to the overall conditions of the presence and absence of DGs are calculated. Additionally, for avoiding an increase in the relays OT, a novel characteristic is proposed. The proposed new characteristic, in addition to a current function (conventional characteristic), has an impedance function. The value of the impedance function is determined from the equivalent impedance (EI) seen by the relay. Consequently, this function is sensitive to the changes in the structure due to the disconnection of DGs. When DG units are disconnected, the impedance function changes in a way that the relay operating speed is improved.

In sum, the most important novelties of this paper are:

- ✓ Presenting a new adaptive characteristic to maintain coordination and to improve the operating speed of overcurrent relays.
- ✓ The adaptive characteristic includes a current and an impedance function. The current function is defined in a similar manner to the conventional characteristic of overcurrent relays, and the impedance function is defined as an exponential function of the Thevenin equivalent impedance seen by the relay. Moreover, to maintain the coordination of overcurrent relays for all conditions of the presence of sources, the proposed adaptive characteristic

is modeled in the relay pairs coordination constraints.

- ✓ The proposed adaptive characteristic can be implemented in networks with different types of DGs (synchronous, inverter-based, etc.).
- ✓ Using local information (voltage and current measured only at the relay location) and no need for communication links and information from other parts of the network.
- ✓ Reducing the number of coordination constraints in the problem of overcurrent relays coordination.

The remaining of the paper is organized as follows. First, the OCRs coordination problem is formulated. The effect of disconnection of DGs on the coordination of relay pairs is then investigated. In addition, the changes in current and EI seen by the relays in case of the disconnection of DGs are investigated, and critical conditions for coordination are identified.

The proposed characteristic is described, and the mechanism of improving the relay operating speed is verified. Finally, the proposed method is implemented on a sample microgrid. By comparing the simulation results of the proposed method with the conventional, the advantages of the proposed method are specified.

2. Coordination problem of OCRs with conventional characteristic

An OCR coordination problem (CP) is a complex optimization problem with a large number of equality and inequality constraints. The purpose of OCR CP is to set current and time of the relays in such a way that, first, the fault occurred at each point of the network is eliminated in the shortest possible time. Secondly, no interference occurs in the operation of the primary and backup relays [33]. In (1), the inverse-time characteristic equation of OCRs is given according to the IEC standard.

$$t_i = \frac{A_i}{(M_i)^{B_i} - 1} \times TDS_i \qquad M_i = \frac{I_{Fault}}{I_{Set_i}} \tag{1}$$

Where t_i is the operating time of the ith relay for the fault current I_{Fault}; TDS_i denotes the time dial setting and I_{Set_i} is the current setting of the ith relay; A_i and B_i are the coefficients determining the slope type of the inverse-time curves. Accordingly, for the normal inverse (NI), very inverse (VI) and extremely inverse (EI) characteristics, coefficient A assumes, respectively, 0.14, 13.5 and 80, and coefficient B assumes, respectively, 0.02, 1 and 2 [34].

Objective function of the CP is usually defined as the sum of the relays OTs according to (2) [35].

$$\min\left\{\sum_{i=1}^{N} t_i\right\} \tag{2}$$

In order to maintain the coordination of the primary and backup relays, the coordination constraint (3) must be considered for all relay pairs; $t_{j,i}$ is the operating time of the jth backup relay of the ith primary relay.

$$t_{j,i}^{l} - t_i^{l} \geq CTI \quad , j=1,2,\dots, N_i \tag{3}$$

Here l denotes the fault location and N_i the number of backup relays of the ith primary relay. The minimum OT of each relay is also limited to t_0 according to (4).

$$t_i \geq t_0 \tag{4}$$

From (5), the current setting range must be determined so that the relay operates correctly for the smallest fault current (I_{fault}^{min}). Moreover, the relay must not have an undesired operation for the maximum load current (I_{load}^{max}) [33 ،36].

$$I_{load}^{max} < I_{Set_i} < I_{fault}^{min} \tag{5}$$

In the CP, the TDS and current setting are unknown. Different methods have been proposed to solve this optimization problem. In this paper, the hybrid method presented in Ref. [35] is used to solve the optimization problem.

When DGs are disconnected, the fault current passing through the primary and backup relays changes, and the violation of the coordination constrain (3) is possible. Consequently, for all given configurations with the disconnection of DGs, it is necessary to consider constraint (3) for all relay pairs in the CP. In this situation, the number of constraints and the OT of the OCRs increases [33].

In this paper, the effect of the disconnection of DG units on the coordination constraints of relay pairs is investigated, and as long as the coordination remains intact, the corresponding constraints are removed from the CP. A new characteristic is then proposed for the OCRs that, in addition to the features of the conventional characteristic, moderates the effect of the disconnection of DG units on the relays OT. The outcome of the two changes in the conventional method (reducing the number of constraints of the CP and relay operation based on the proposed characteristic) is a shorter relay OT, improvement in operating speed of the primary and backup protections.

3. Effect of DG disconnection on OCRs coordination

The disconnection of DGs changes the fault current flowing through relay pairs. According to the conventional characteristic (1), the relay OT changes and the relays coordination in (3) may be lost. In this section, to address this problem, the effect of the disconnection of

DGs on the coordination of OCRs with the conventional characteristic is analyzed. In the following, with the help of the conducted analyses, a characteristic that has less sensitivity to the disconnection of DGs is proposed.

In this paper, the concept of base case describes the structure that includes all DGs. In the following, the effect of the disconnection of DGs on the fault current passing through a relay, the relay OT and relay pairs coordination is evaluated. According to (6), in order to evaluate the coordination, the index DCTI is defined as the difference between the OTs of the backup and primary relays minus CTI.

$$\mathrm{DCTI}_{j,i} = t_{j,i} - t_i - \mathrm{CTI} \tag{6}$$

DCTI can assume one of the following three values:

- **Zero:** in this case, there is a full coordination in the relay pair, and the backup protection shows no delay.
- **Greater than zero:** in this case, there is a full coordination in the relay pair; however, backup protection delays longer than the value of CTI.
- **Smaller than zero:** in this case, the coordination constraint is violated.

3.1. Changes in fault current through relay pairs

In Fig. 1, the general schematic of a doubly-fed power system is shown. This system has a DG and a relay pair (R1 and R2). The DG, which is connected to the bus between the relays, injects the current I_{DG} into the bus B_2. The settings of relays R1 and R2 are determined in the presence of the DG.

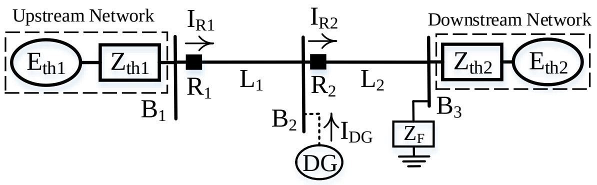

Fig. 1. Single line diagram of a power system with DG.

In presence of DG, if a fault with impedance Z_F occurs at the end of the line L_2, the current through the relay pair is calculated from (7) and (8).

$$I_{R2} = \frac{E_{th1} + I_{DG}(Z_{th1} + Z_{L1}) - \frac{Z_F}{Z_{th2}+Z_F} \times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}} \tag{7}$$

$$I_{R1} = \frac{E_{th1} - I_{DG}\left(Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}\right) - \frac{Z_F}{Z_{th2}+Z_F} \times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}} \tag{8}$$

In the case of the disconnection of the DG, the fault currents through R1 and R2 are equal for a fault at the end of line L_2, and can be calculated using (9).

$$I'_{R1} = I'_{R2} = \frac{E_{th1} - \frac{Z_F}{Z_{th2}+Z_F} \times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}} \tag{9}$$

By comparing equations (7) and (8) with equation (9), it can be concluded that, if the DG is disconnected, the fault current of the primary relay, I'_{R2}, decreases (compared to the base case current (I_{R2}) in the presence of DG), and the fault current of the backup relay (I'_{R1}) increases (compared to the base case current, I_{R1}).

Table I. Fault current passing through relay pairs in different cases of DG disconnection.

Location of DG	Relay label	Fault current flowing through relays	Changes	Value of DCTI
Before relay pair	R1	$\frac{E_{th1}+I_{DG}Z_{th1}-\frac{Z_F}{Z_{th2}+Z_F}\times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}}$	Decrease	Positive
	R2			
After relay pair	R1	$\frac{E_{th1}-\frac{E_{th2}+I_{DG}Z_{th2}}{Z_{th2}+Z_F}\times Z_F}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}}$	Increase	Negative
	R2			
Between relays	R1	$\frac{E_{th1} - I_{DG}\left(Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}\right) - \frac{Z_F\times E_{th2}}{Z_{th2}+Z_F}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}}$	Increase	Negative
	R2	$\frac{E_{th1}+I_{DG}(Z_{th1}+Z_{L1}) - \frac{Z_F}{Z_{th2}+Z_F}\times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}}$	Decrease	
Base case (presence of DG)	R1	$\frac{E_{th1} - \frac{Z_F}{Z_{th2}+Z_F}\times E_{th2}}{Z_{th1}+Z_{L1}+Z_{L2}+\frac{Z_{th2}\times Z_F}{Z_{th2}+Z_F}}$	---	---

In the conventional characteristic, the settings of relays R1 and R2 are the same and unchanged in both the absence and presence of the DG.

In the case of overcurrent relays coordination problem, the optimal relays settings are determined so that, besides maintaining the coordination of all relay pairs, the operating speed of the primary and backup protection is maximized. Therefore, the OTs of the primary and backup relays are usually set to the minimum possible values. Accordingly, there is usually only a minimum coordination time interval (CTI) between the OTs of the primary and backup relay pair (it is attempted that the value of DCTI vanishes). Some events (such as the disconnection of DGs) increase the OT of the primary relay and decrease the OT of the backup relay, so miscoordination may occur (negative DCTI). From (10), in the event of the DG disconnection, the difference between the OTs of the relays decreases, DCTI may become negative and a miscoordination occurs.

$$\mathrm{DCTI'}=(t_{R1}\downarrow - t_{R2}\uparrow) - \mathrm{CTI} \Rightarrow \mathrm{DCTI'}<\mathrm{DCTI} \quad (10)$$

Similarly, the effect of the disconnection of DG connected to buses before and after the relay pair is investigated, and the results are presented in Table I. According to this table, the disconnection of a DG either between the relays or after the relays can lead to miscoordination.

3.2. Changes in EI seen by relay pairs

In order to reduce the effect of the disconnection of DGs on relay pair coordination, a function describing the EI seen by relay is used in the relay characteristic. Variations of impedance function must be opposite to the variations of its current function so that the effect of disconnection of DGs is reduced and the coordination is maintained. The EI seen by the relay is equal to the impedance of the upstream network. In Fig. 1, the EI seen by the primary relay R2 and the backup relay R1, when the DG is connected to bus B2 and before the fault occurs, are defined according to (11) and (12).

$$Z_{th}^{R2}=Z_{L2}+Z_{th2} \quad (11)$$

$$Z_{th}^{R1}=Z_{L1}+\left(Z_{DG}||Z_{th}^{R2}\right)=Z_{L1}+Z_{DG}||(Z_{L2}+Z_{th2}) \quad (12)$$

However, if the DG is disconnected, the EI seen by the relay pair changes to the values given by (13) and (14).

$$Z'^{R2}_{th}=Z_{L2}+Z_{th2} \quad (13)$$

$$Z'^{R1}_{th}=Z_{L1}+Z'^{R2}_{th}=Z_{L1}+Z_{L2}+Z_{th2} \quad (14)$$

These impedances are measured continuously before the fault occurs (under steady-state conditions). By comparing (11) and (13), it can be concluded that the EI seen by the primary relay R2 has not changed. Moreover, the comparison of (12) and (14) shows an increase in the EI seen by the backup relay R1. In the following, the effect of the disconnection of DGs on the EI seen by the relays is investigated. For this purpose, in Table II, changes in the EI seen by the relay pair are summarized for all possible configurations of DG disconnection.

Table II. EI seen by relay pair for all possible configurations of DG disconnection

Location of DG	Relay label	Before disconnection	After disconnection	Changes
Before relay pair	R1	$Z_{L1}+Z_{L2}+Z_{th2}$		---
	R2	$Z_{L2}+Z_{th2}$		---
After relay pair	R1	$Z_{L2}+Z_{L3}+(Z_{th2}\|\|Z_{DG})$	$Z_{L2}+Z_{L3}+Z_{th2}$	Increase
	R2	$Z_{L3}+(Z_{th2}\|\|Z_{DG})$	$Z_{L3}+Z_{th2}$	Increase
Between relays	R1	$Z_{L2}+Z_{DG}\|\|(Z_{L3}+Z_{th2})$	$Z_{L2}+Z_{L3}+Z_{th2}$	Increase
	R2	$Z_{L3}+Z_{th2}$	$Z_{L3}+Z_{th2}$	---

According to the results of Table I and Table II, a comparison is made between the changes in current and impedance seen by the relay pair in the presence and absence of the DG.

- **Disconnection of DG connected to the bus just after the relay pair**

If this DG is disconnected, in the event of a fault, currents in both the primary and backup relays increase. An increase in the current leads to a decrease in the OT of the relay pair, a negative DTCI and miscoordination. Moreover, due to this disconnection, the EI seen by both the primary and backup relays also increases before the fault occurs. Therefore, if the impedance function, which is directly related to the Thevenin equivalent impedance before the fault, is added to the relay characteristic, the increase in the impedance function compensates for the decrease in the current function, and the value of DTCI is improved.

- **Disconnection of DG connected to the bus between the relays**

If this DG is disconnected, in the event of a fault, the fault current of the primary relay decreases and the fault current of the backup relay increases. From (10), the value of DCTI is negative and there may be a miscoordination. Furthermore, before the fault occurs, the EI seen by the primary relay has not changed, while the EI seen by the backup relay has increased. Therefore, if the impedance function is directly related to the impedance, the increase of the impedance function of the backup relay compensates for the decrease of the current function, and the value of DTCI is improved.

- **Disconnection of DG connected to the bus just before the relay pair**

since DTCI index is positive, according to Table I, miscoordination does not occur. Due to no change in the EI seen by the relay pair before the occurrence of the fault, the impedance function does not affect the relay characteristic. As a conclusion of the analyses for the three configurations corresponding to the disconnection of DGs, it is rational that an impedance function, which is directly related to the EI seen by the relays, is added to the conventional characteristic of the OCR. This EI must be calculated continuously and online before the occurrence of fault in a steady-state condition. In this way, once the DG is disconnected, the EI seen by the relay is updated. In the event of a fault, the value of this impedance is used in the proposed characteristic.

4. Calculation of EI seen by relay

The EI seen by the relays before the occurrence of fault is calculated using the method proposed in [37], and the corresponding model presented in Fig. 2. These calculations are performed continuously in an online manner, and the steady-state information of the network is used. In accordance with Fig. 2, after several measurements of voltage and current at the relay location, the EIs of the upstream and downstream are calculated under load variation. The impedance used in the proposed characteristic (Z_2) is calculated from (15).

$$Z_2 = \frac{COV[\Delta\overline{V}\Delta Z_L]}{COV[\Delta\overline{I}_R \Delta Z_L]} \tag{15}$$

Where $\Delta\overline{V}$ and $\Delta\overline{I}_R$ are the variation of voltage and current sampled by the relay, and ΔZ_L is the random load variation.

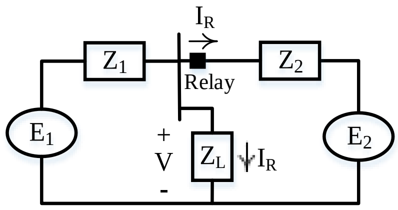

Fig. 2. Single-phase equivalent circuit of power system seen by relay [37].

5. Proposed adaptive characteristic

In this section, a new characteristic is presented for the operation of the OCRs in accordance with equation (16).

$$t_{op} = f(I) \times f(Z_{th}) = \frac{A \times TDS}{\left(\frac{I_F}{I_{set}}\right)^B - 1} \times (e^{Z_{th}})^K \tag{16}$$

This characteristic consists of the product of two functions. One function that corresponds to the current flow through the relay and the other corresponds to the EI from a point on the bus near the relay. The function corresponding to the relay current is exactly the same as the conventional inverse time characteristic of the OCRs. Additionally, the function corresponding to impedance is an exponential function in terms of the EI seen by the relay (Z_{th}) under steady-state just before the occurrence of the fault. To change the effect of the impedance function during the relay operation, the power factor K is added to this function.

The impedance function is intended to improve the performance of the relays in different structures. If the value of K is set to zero, the proposed characteristic is reduced to the conventional characteristic of the overcurrent relays.

In Fig. 3, the algorithm of the adaptive relay with the proposed characteristic is shown in the form of a flowchart. The required information, including the optimal relay settings, is loaded into it. These settings include I_{set}, TDS and coefficients K, A and B, which are determined offline by solving the optimal CP, i.e., the method proposed in Section 7.

Once a fault occurs, if the value of the impedance function is known and constant, then the characteristic of equation (16) is reduced to the conventional characteristic of overcurrent relays (equation (5)). Consequently, in the base structure, where the impedance seen by the relays is known and constant, the relays coordination problem can be solved and optimized by conventional methods with the exception that a parameter (K) is added to the unknowns of the problem. The structure of the proposed chromosome for the hybrid method in [35] is according to Fig. 4.

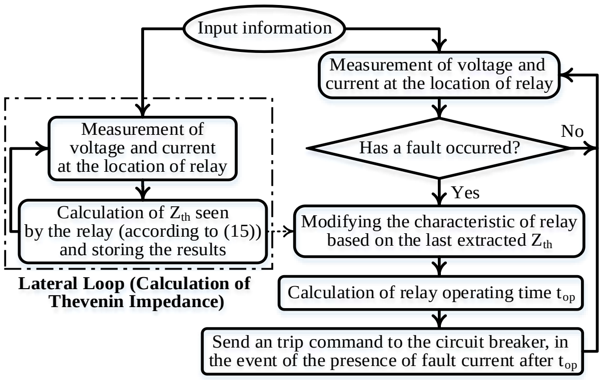

Fig. 3. Flowchart of the algorithm of proposed adaptive relay.

I_{set_1}	B_1	K_1	I_{set_2}	B_2	K_2	$\cdots$	I_{set_N}	B_N	K_N

Fig. 4. Proposed chromosome structure for optimally solving the overcurrent relays coordination problem by the hybrid method [35].

To ensure the optimal global solution, the number of iterations of the proposed algorithm is sufficiently large. Furthermore, by multiple executions of the algorithm and obtaining the same solution, the optimal global solution is guaranteed.

As shown in Fig. 3, the proposed adaptive relay has two loops that are evaluated independently. In the lateral loop, just the EI of the network seen by the relay is calculated. In the main loop, the fault is detected if IF be greater than Iset.

Then, based on the last Z_{th} of the lateral loop output, the value of the impedance function is determined so that the relay OT is modified. Finally, when the values of current and impedance functions are known, the relay OT is determined.

If the flow in the lateral loop is transferred to the main loop, this flow will be executed moment-by-moment. Although the accuracy of the Thevenin equivalent is satisfactory in this case, due to the increased processing volume of this loop, its execution time increases and its efficiency decreases.

However, if the lateral loop is executed independently from the main loop, the execution time of the main loop is reduced, and the fault detection speed and relay performance are increased. Assuming the n-1 criterion, the last output of the lateral loop before fault occurrence is valid at the time of fault occurrence. Then, only the output of the lateral loop is sent to the main loop and is used for detecting faults and calculating operating times.

In the lateral loop, the voltage of the bus at the location of the relay, line current and the current of the load connected to the bus at the location of the relay are continuously sampled. In this loop, variations in voltage (ΔV^i), current ($\Delta I_{Load}{}^i$), load impedance ($\Delta Z_{Load}{}^i$) and the current through the relay ($\Delta I_{Line}{}^i$) for the time window T_D is calculated and stored. Then, using (15), the EI seen by the relay is calculated and stored for using in the main loop. This loop is evaluated continuously and stores the newest Z_{th} at any time.

The main loop constantly samples the current through the relay and detects the occurrence of a fault. When a fault is detected, by using the values of the fault current and EI seen by the relay (which has been calculated in the lateral loop), the relay operating time (t_{op}) can be obtained. The fault situation must be checked up to t_{op}. Indeed, if the relay acts as a backup, and the primary relay operates before t_{op}, the backup relay will not operate. If the fault persists after t_{op}, the trip command will be sent to the corresponding circuit breaker (CB).

The proposed adaptive characteristic can be used in digital overcurrent relays in distribution networks since it only needs the information (voltage and current) at the relay location (current and voltage transformers are installed for conventional directional overcurrent relays). Accordingly, there is no need to build infrastructures, communication links and data exchange with other parts of the network; that is, the implementation cost of the proposed approach is minimal.

Therefore, by applying the proposed method, while maintaining coordination, the OTs of the overcurrent relays in both the base structure and other structures of the presence of DG sources are improved. Consequently, reliability indices (e.g., in terms of unexpected outages, etc.) will also be improved.

In this paper, other uncertainties affecting the measured current, including the effect of current transformers and line impedance, are not considered.

To evaluate the relay operating speed, the computation time required for the proposed algorithm is divided into two parts, i.e., online and offline calculations:

- In offline calculations, the optimal relays setting are calculated. These calculations need to be executed only once and have no effect on instantaneous relay operation.
- Online calculations that are performed in the main and lateral loops and the procedures in this part are continuously repeated. The lateral loop requires about 40 consecutive phasor measurements with approximately one second to calculate the Thevenin equivalent. However, this process is not done during a fault, it is done in a separate algorithm (lateral loop). The main loop detects faults and applies the EI seen to the relay function, which ultimately requires 0.1 cycles to perform its computations.
- The duration of fault detection depends only on the execution time of the main loop, and just the last output of the side loop is used. Conseqently, the performance of the proposed adaptive algorithm has a very slight delay than that of the conventional overcurrent relays algorithm.

6. Effect of DG disconnection on coordination of relays with the proposed characteristic

In this paper, two kinds of coordination constraint are considered in the OCR coordination. Constraints related to the main structure of the network (with the presence of all DGs) and constraints related to the structures left after the disconnection of each DG. Therefore, if all of these constraints are included in the CP, the relay pairs coordination in all structures is established.

In the following, it is shown that if the conventional characteristic is used, the relays OT increases significantly due to the addition of different structures constraints. However, the proposed characteristic reduces the OT.

According to the Table I, the most critical constraint is the disconnection of the DG that is located just between two relays. The most critical constraint has the greatest effect on the relay OT. If the conventional characteristic is used, the coordination constraint for this case can be written as follows:

$$DCTI_{j,i}=\frac{A_j}{\left(\frac{I_{F_j}}{I_{set_j}}\right)^{B_j}-1}\times TDS_j-\frac{A_i}{\left(\frac{I_{F_i}}{I_{set_i}}\right)^{B_i}-1}\times TDS_i-CTI\geq 0 \tag{17}$$

It is assumed that the type of the characteristic curve (coefficients A and B) and the current setting of relays are fixed, and only TDS parameters can be varied. In the case of disconnection of the DG between the relays, the currents of primary and backup relays decreases and increases, respectively. Consequently, DCTI is obtained using (18).

$$DCTI'_{j,i}=\downarrow f\left(\uparrow I_{F_j}\right)\times TDS_j-\uparrow f\left(\downarrow I_{F_i}\right)\times TDS_i-CTI \tag{18}$$

Due to the reduction in the backup relay OT and the increase in the primary relay OT, compared to the base case, DCTI index becomes negative and the coordination is violated.

The strategy for maintaining coordination in this conditions is to either increase TDS_j or decrease TDS_i. It is possible to decrease TDS_i to the extent that the relay OT is not less than the minimum value of t_0. Moreover, due to the need for a faster protection system, the relays TDS_i are determined, beforehand, at the smallest possible values. Consequently, the only strategy for maintaining the coordination in the event of the disconnection of the DG is to increase the TDS_j. If (18) is set to zero in the most critical condition, the minimum value of TDS_j^{Conv} for maintaining the relay pair coordination is obtained from (19).

$$TDS_j^{Conv} = \frac{\left(CTI + \uparrow f(\downarrow I_{F_i}) \times TDS_i\right)}{\downarrow f(\uparrow I_{F_j})} \qquad (19)$$

Therefore, both TDS_j and the relay OT increase. If the proposed characteristic is used, (20) is the coordination constraint of the OCR pair.

In the event of the disconnection of a DG connected to the bus between the relays, the fault current through the primary relay (I_{F_i}) decreases and through the backup relay (I_{F_j}) increases. In addition to current variations, the EI seen by the backup relay increases and the EI seen by the primary relay remains unchanged. In (21), the results of all these changes are presented.

$$DCTI_{j,i} = \frac{A_j \times TDS_j^{pro}}{\left(\frac{I_{F_j}}{I_{set_j}}\right)^{B_j} - 1}\left(e^{Z_j^{th}}\right)^{K_j} - \frac{A_i \times TDS_i^{pro}}{\left(\frac{I_{F_i}}{I_{set_i}}\right)^{B_i} - 1}\left(e^{Z_i^{th}}\right)^{K_i} - CTI \geq 0 \qquad (20)$$

$$DCTI'_{j,i} = \downarrow f\left(\uparrow I_{F_j}\right) \times TDS_j \times \uparrow f\left(\uparrow Z_j^{th}\right) - \uparrow f(\downarrow I_{F_i}) \times TDS_i \times f\left(Z_i^{th}\right) - CTI \geq 0 \qquad (21)$$

Obviously, an increase in the backup relay impedance function to some extent compensates the decrease in the backup relay current function. Consequently, TDS_j requires a moderate increase compared to the conventional characteristic. In the same way, if (21) is set to zero for the most critical condition, according to (22), the minimum value of the backup relay time dial coefficient (TDS_j^{pro}) is calculated to maintain the relay pair coordination in the event of DG disconnection.

$$TDS_j^{pro} = \frac{CTI + \uparrow f(\downarrow I_{F_i}) \times TDS_i \times f\left(Z_i^{th}\right)}{\downarrow f\left(\uparrow I_{F_j}\right) \times \uparrow f\left(\uparrow Z_j^{th}\right)} \qquad (22)$$

In this equation, if the proposed characteristic is used, the impedance function in the denominator increases and TDS_j^{pro} decreases. By comparing (19) and (22), it can be concluded that, in general, the OT of the relays with the proposed characteristic is shorter in the event of the disconnection of DGs.

7. Proposed method for relay CP

Input information for the flowchart in Fig. 3, includes relay settings, such as TDS and I_{set} as well as coefficients A, B and K. The coefficients A and B are fixed with values 80 and 2, respectively. Moreover, the relays current setting (I_{set}) is determined based on the maximum load current, while TDS and K are obtained by solving the optimal CP.

The optimal CP is solved once in offline mode. In this problem, all coordination constraints corresponding to the disconnection of DGs are included in the problem to obtain solutions that ensure coordination in all circumstances.

If the conventional characteristic is used, the variables of the CP are only relays TDS, and the CP is in accordance with the formulation in Section 2 ; i.e., it can be converted into a linear programming CP, which can be easily solved. In the proposed characteristic, in addition to TDS, K is also unknown and the problem is nonlinear. To solve this problem, the hybrid method of Ref. [35] is used. Besides proposing a new characteristic, the number of coordination constraints (NCCs) that must be included in the CP has also decreased.

In the conventional method of OCRs coordination, the coordination constraint is defined so that all structures (due to the disconnection of DGs) are included. Accordingly, in accordance with (23), the NCCs in the conventional method is equal to the product of the total number of relay pairs and the number of possible structures resulted from the disconnection of DGs plus unity (the base case with the presence of all DG).

$$\text{NCCs in conventional method} = N_P \times (N_{DG} + 1) \qquad (23)$$

N_P is the total number of relay pairs and N_{DG} is the total number of changes in structurs due to the disconnection of DGs.

In the proposed method, however, all coordination constraints of the base case and a critical constraint associated with each structure are considered (the latter is related to the DG between the primary/backup relays). Because each DG is located between two relays, according to (24), the NCCs in the CP of the proposed method is equal to the sum of the number of relay pairs and twice the number of changes in structures resulting from the disconnection of DG units.

$$\text{NCCs in proposed method} = N_P + 2N_{DG} \qquad (24)$$

By comparing (24) and (23), the decrease in the NCCs of the proposed method is clear.

8. Simulation results

For numerical evaluation of the proposed method, the microgrid in Fig. 5 has been simulated in MATLAB. This network is connected to the main distribution grid, with a short circuit level of 1000 MVA, through a $120^{\mathrm{kV}}/25^{\mathrm{kV}}$ transformer. The microgrid consists of six lines, 12 OCRs and four DGs. DG1 and DG3 are synchronous generators, DG2 is a DFIG and DG4 is a wind turbine with electronic converter. Information about lines, transformers, DGs and loads is given in [38].

The configuration of microgrid in Fig. 5 can be either radial or ring. For each configuration, the optimal settings of the OCRs are determined by solving the optimization problem based on both conventional and proposed methods. Coordination constraints include the constraints of the base case (with the presence of all DGs) and the critical constraints of the structures with some disconnected sources. The base case comprises all DGs in each configuration. Then, using these settings, the OTs of relay pairs are calculated and compared in all cases of the presence and absence of DGs.

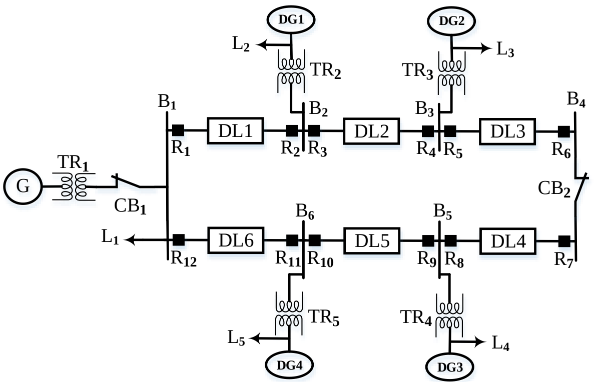

Fig. 5. Schematic of the microgrid under study [38].

In these calculations, the assumptions are as follows:

- CTI is 0.3 seconds [35]
- The values of K and relays TDS are continuous and positive [1].
- The relay coordination problem is solved based on the currents of faults exactly next to the primary relays [33].
- Coefficients A and B are fixed and equal to 80 and 2, so that a better comparison can be made between the results of the two methods.
- Based on the n-1 contingency criterion, it is assumed that the simultaneous connection or disconnection of sources cannot occur 1 second before the fault. In practice, for updating the Thevenin impedance seen by the relay, about 40 consecutive samples of voltage and current are required (in approximately 1 second) [37].

8.1. Relays OT in radial configuration

Radial configuration is activated when CB_2 is opened, and only the operation of the relays R1, R3 and R5 are investigated. The most critical constraint for the pair R3 and R5 is the disconnection of DG2. In Table III, for each relay pair, the fault currents through the relays for a fault occurring exactly in front of the primary relay are presented. In

Table **IV**, the impedances seen by the relays are shown in the presence and absence of DG2.

Table III. Fault current through relay pairs of radial system in the event of three-phase fault occurrence in front of the primary relays.

Number of			Base case (presence of DG2)		Absence of DG2	
Relay pair	Backup relay	Primary relay	Backup relay	Primary relay	Backup relay	Primary relay
1	3	5	8.3167	10.3738	8.3527	8.3527
2	1	3	10.3738	12.8289	10.8222	12.8610

Table IV. EIs seen by relays (in perunit).

	$\mathbf{R_1}$	$\mathbf{R_3}$	$\mathbf{R_5}$
Presence of DG2	0.2997	0.536	∞
Absence of DG2	0.3809	0.9206	∞

In the following, the CP is solve one time for all OCRs with the conventional characteristic, and another time for relays with the proposed characteristic; relays settings are then obtained and presented in Table V.

Table V. Proposed and conventional settings of relays in radial configuration.

Relay number	**Proposed characteristic**					**Conventional characteristic**			
	TDS	$\boldsymbol{I_{set}}$	**A**	**B**	**K**	**TDS**	$\boldsymbol{I_{set}}$	**A**	**B**
1	0.2387	1.3	80	2	1.14	0.3681	1.3	80	2
3	0.1491	1.3	80	2	0.07	0.1589	1.3	80	2
5	0.0078	1.3	80	2	0	0.0078	1.3	80	2

The hybrid algorithm is converged so that the relay setting current has its maximum possible value, i.e., 1.3 times the nominal current. However, coefficients K are determined with regard to the combination of the relay pairs and their interactions. For example, since relay R5 is not the backup of any relay, its K is equal to zero so that the impedance function does not hinder its operation.

At the same time, with given coefficients A, B, K and $\mathrm{I_{set}}$, the optimal values of coefficients TDS are calculated by solving the linearized problem so that while maintaining the relays coordination, their OTs are minimized.

Using the settings in Table V, the relays OTs are calculated in the base case and in the absence of DG2. The results are presented in Table VI. As can be seen, the total OTs of the primary and backup relays are the same in the proposed and conventional characteristics in the absence of DG2.

However, in the base case, the OT of backup relay R3 in relay pair (3, 5) decreases from 0.3184 seconds to the minimum value of 0.3100 seconds, and the OTs of both primary and backup relays (1, 3) decrease from 0.1319 and 0.4699 seconds to, respectively, 0.1284 and 0.4284 seconds. Consequently, the values of total OT of the primary and backup relays for the proposed characteristic show, respectively, 2.47% and 6.33% reduction compared to the conventional characteristic.

Additionally, the total DCTI decreases from 0.0464 seconds to the minimum possible value, 0.

Table VI. operation Time (secs) of relay pairs with the settings in Table V.

			Base case (Presence of DG2)			Absence of DG2		
	Backup relay	**Primary relay**	t_{op}^{b}	t_{op}^{p}	**DCTI**	t_{op}^{b}	t_{op}^{p}	**DCTI**
Conventional	3	5	0.3184	0.0100	0.0084	0.3155	0.0155	0
	1	3	0.4699	0.1319	0.0380	0.4312	0.1312	0
	Total		**0.7883**	**0.1419**	**0.0464**	0.7467	0.1467	0
Proposed	3	5	0.3100	0.0100	0	0.3155	0.0155	0
	1	3	0.4284	0.1284	0	0.4312	0.1312	0
	Total		**0.7384**	**0.1384**	**0**	0.7467	0.1467	0

8.2. Relays OT in ring configuration

When CB2 is closed, the microgrid is put into the ring configuration. In the case of ring configuration, the relays at both sides of the line are directional.

To calculate the relays settings, first the EI seen by the relays and the fault current through the relays are calculated in all structures of the presence and absence of DGs. Then, by solving the optimal CP of the OCRs, the relays settings are calculated for both the conventional and proposed methods, which are presented in Table VII. The operating times (t_{op}) presented in this table, are calculated for the faults exactly in front of the primary relays in the base case.

According to these results, it is observed that the OTs of the relays with the proposed characteristic is shorter. For example, in the event of faults exactly in front of R6, its OT in base case is 0.458 s, based on the conventional characteristic. However, if this relay operates according to the proposed characteristic, its OT is reduced by 49.69%, to 0.2304 s. In general, the total OT of the primary relays for the base case, is 3.3474s in conventional method, and 2.1375s in the proposed method, which shows a reduction of 36.15%.

In Fig. 6, OTs of R4 and R6 are shown using the conventional characteristic for the occurrence of fault at various points in the line DL-2 for different structures of the presence and absence of DGs. In Fig. 7, the relay OT is shown using the proposed characteristic.

The relays OTs in different structures of the presence of DGs using either the proposed or Ref. [32] and conventional methods are given in

Table **VIII**. These OTs are calculated for all relay pairs in the event of fault at the beginning or end of the line.

Table VII. Optimal settings of relays, considering the coordination constraints of all structures for the presence and absence of DGs.

Relay number	**A**	**B**	I_{set}	**Conventional characteristic**		**Proposed characteristic**		
				TDS	t_{op}	**K**	**TDS**	t_{op}
1	80	2	0.5	4.011	0.159	2.153	1.4742	0.1072
2	80	2	0.5	0.323	0.147	0	0.2859	0.1304
3	80	2	0.5	2.336	0.299	5.4701	0.4289	0.1882
4	80	2	0.5	0.608	0.286	25.0061	0.0152	0.1858
5	80	2	0.5	1.478	0.324	9.3773	0.1232	0.2267
6	80	2	0.5	0.893	0.458	14.0659	0.0497	0.2304
7	80	2	0.5	0.893	0.458	25.0061	0.0090	02304
8	80	2	0.5	1.478	0.324	4.6886	0.3569	0.2267
9	80	2	0.5	0.608	0.286	25.0061	0.0152	0.1858
10	80	2	0.5	2.336	0.299	2.3443	0.8679	0.1882
11	80	2	0.5	0.323	0.147	0	0.2860	0.1304
12	80	2	0.5	4.011	0.159	1.5629	1.1825	0.1072
Total time (sec)					**3.3474**	**Total time (sec)**		**2.1375**

In the following, the OTs of R4 and R6 are investigated to compare the conventional and proposed methods.

From Table I, the most critical condition for the operation of R4 and R6 is the disconnection of DG2. In the optimization problem, the relays settings are determined in such a way that in the critical condition (disconnection of DG2), the distance between the two OT characteristic curves of the primary and backup relays (CTI) is minimized. Accordingly, in other structures (non-critical structures), the time interval between the primary and backup relays characteristics is larger. This can be verified for the relays R4 and R6 with conventional characteristic in Fig. 6.

However, in the proposed characteristic, the impedance function for the occurrence of fault in different structures changes so that the total OT of the primary and backup relays is reduced compared to the case of the conventional characteristic. Accordingly, in Fig. 7, it can be observed that, not only the OT of R4 and R6 in the critical structure decreases, but there is also a significant reduction in the OT of these relays in other structures.

As an example, if the conventional characteristic is considered (inset in Fig. 6), the OTs of the relays R4 and R6 for a fault in the middle of the line DL-2 and in the event of the disconnection of DG2 are 0.93 and 1.36s, respectively; if DG3 is disconnected, these values are 0.54 and 2.35s, respectively. However, if the proposed characteristic is used, as shown in Fig. 7, the OTs of relays R4 and R6 for a fault in the middle of the line DL-2 and in the absence of DG2 are, respectively, 0.59 and 1.02 s, which are reduced by 36.56% and 25%; if DG3 is disconnected, these values are 0.33 and 2.01 s, which are reduced by 31.48% and 48.49%, respectively. It is worth noting that the time difference in the operation of the relay pair in the absence of DG2 is 1.81s for the conventional method, and 0.83s for the proposed method, which shows a 54.14% reduction.

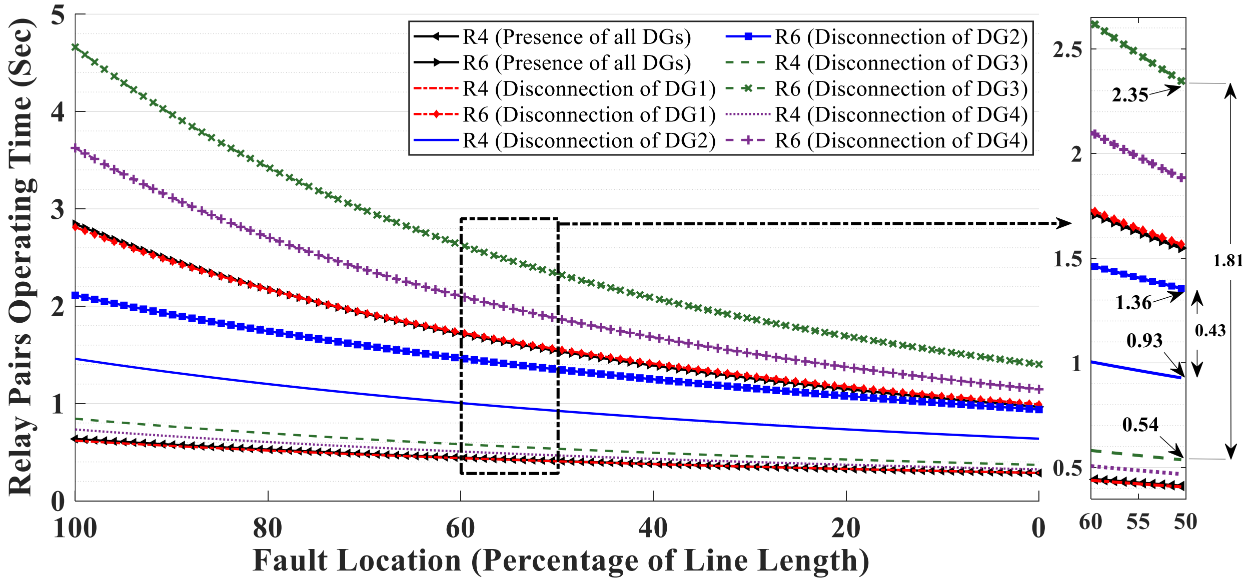

Fig. 6. Evaluation of coordination of primary and backup (R4, R6) with the ref [32] and conventional characteristic at different cases of presence of DGs.

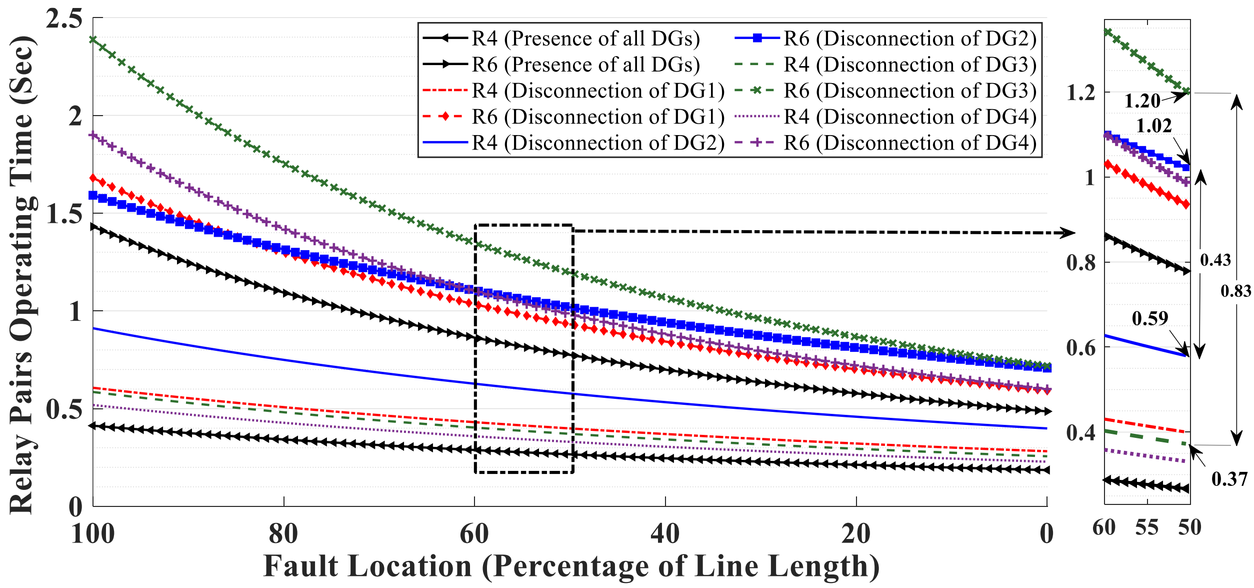

Fig. 7. Evaluation of coordination of primary relay R4 and backup relay R6 with the proposed characteristic at different cases of presence of DGs.

In sum, from Fig. 6 and Fig. 7, the following results (advantages of the proposed method over the conventional method) can be seen:

- By comparing the curves of relay pair R4 and R6 in Fig. 6 and the corresponding curves in Fig. 7, it can be concluded that the operating speed of the relay pair with the proposed characteristic is better than that with the conventional characteristic.
- The operating speed of the relay pair is increased in the base structure under which the system operates most of the time.

In the conventional method (Fig. 6), it can be seen that the operating time curve of primary relay R4 (left to right triangles on black solid line) has the lowest level (shorter time), while the operating time curve of backup relay R6 in the base structure (right to left triangles on black solid line) is on top of the curve corresponding to the structure of DG2 disconnection (the most critical structure shown by squares on blue solid line).

However, in the proposed method (Fig. 7), the OT curves of both relays R4 and R6 in the base structure (triangles on black solid lines) are beneath their corresponding curves in other structures.

- The value of DCTI of relay pair R4 and R6 is decreased in all structures.

This improvement can also be deduced if the distance between the two OT curves of the relay pair in each structure of Fig. 6 is compared with that of corresponding curves in Fig. 7.

Table VIII. Relay pairs OT with the conventional characteristic and settings of Table VII in different structures at the presence of DGs.

			Method of ref [32] and conventional characteristic													Proposed characteristic													CTDCTI (%)
		PR number	1	2	3	4	5	6	7	8	9	10	11	12	Total	1	2	3	4	5	6	7	8	9	10	11	12	Total	
		BR number	11	4	1	6	3	8	5	10	7	12	9	2		11	4	1	6	3	8	5	10	7	12	9	2		
Occurrence of fault in front of PR	PAD	PR	0.16	0.15	0.3	0.29	0.32	0.46	0.46	0.32	0.29	0.3	0.15	0.16	3.35	0.11	0.13	0.19	0.19	0.23	0.23	0.23	0.23	0.19	0.19	0.13	0.11	2.14	36.1
		BR	0.46	0.66	0.73	0.97	0.84	0.76	0.76	0.84	0.97	0.73	0.66	0.46	8.82	0.41	0.43	0.49	0.49	0.53	0.53	0.53	0.53	0.49	0.49	0.43	0.41	5.74	34.9
		DCTI	0	0.22	0.13	0.38	0.21	0	0	0.21	0.38	0.13	0.22	0	1.88	0	0	0	0	0	0	0	0	0	0	0	0	0	100
	DDG1	PR	0.16	0.34	0.42	0.29	0.4	0.47	0.54	0.33	0.32	0.31	0.16	0.18	3.92	0.17	0.3	0.26	0.28	0.28	0.28	0.29	0.26	0.23	0.21	0.14	0.12	2.83	27.8
		BR	0.54	0.64	0.72	0.99	1.08	0.78	0.9	0.87	1.15	0.77	0.77	1.44	10.63	0.48	0.63	0.76	0.59	0.68	0.6	0.64	0.57	0.62	0.54	0.54	1.28	7.92	25.5
		DCTI	0.08	0	0	0.4	0.38	0.01	0.05	0.24	0.52	0.16	0.3	0.96	3.1	0.01	0.03	0.19	0.01	0.1	0.02	0.05	0.02	0.09	0.04	0.1	0.85	1.51	51.3
	DDG2	PR	0.16	0.25	0.3	**0.64**	0.52	0.46	0.67	0.33	0.37	0.31	0.18	0.17	4.35	0.14	0.22	0.35	**0.4**	0.36	0.35	0.35	0.28	0.26	0.21	0.16	0.12	3.19	26.7
		BR	0.63	1.53	0.74	**0.94**	0.82	0.76	1.11	0.86	1.4	0.76	0.88	0.96	11.38	0.56	0.96	0.65	**0.71**	0.96	0.66	0.76	0.59	0.73	0.55	0.61	0.85	8.57	24.7
		DCTI	0.16	0.99	0.14	**0**	0	0	0.14	0.23	0.73	0.15	0.4	0.49	3.43	0.11	0.44	0	**0.01**	0.31	0.01	0.12	0	0.17	0.04	0.15	0.43	1.79	47.8
	DDG3	PR	0.17	0.18	0.31	**0.37**	0.33	0.67	0.46	0.52	0.64	0.3	0.25	0.16	4.35	0.13	0.16	0.23	**0.26**	0.35	0.34	0.48	0.36	0.4	0.25	0.22	0.13	3.29	24.4
		BR	0.96	0.88	0.76	**1.4**	0.86	1.11	0.76	0.82	0.94	0.74	1.53	0.63	11.38	0.85	0.61	0.57	**0.72**	0.65	0.77	0.81	0.67	0.97	0.59	0.96	0.56	8.72	23.4
		DCTI	0.49	0.4	0.15	**0.73**	0.23	0.14	0	0	0	0.14	0.99	0.16	3.43	0.42	0.15	0.04	**0.16**	0	0.13	0.03	0.02	0.27	0.04	0.44	0.13	1.83	46.6
	DDG4	PR	0.18	0.16	0.31	0.32	0.33	0.54	0.47	0.4	0.29	0.42	0.34	0.16	3.92	0.13	0.14	0.22	0.23	0.28	0.28	0.32	0.28	0.28	0.26	0.3	0.14	2.87	26.8
		BR	1.44	0.77	0.77	1.15	0.87	0.9	0.78	1.08	0.99	0.72	0.64	0.54	10.63	1.28	0.54	0.56	0.6	0.6	0.64	0.65	0.68	0.68	0.64	0.63	0.48	7.95	25.2
		DCTI	0.96	0.3	0.16	0.52	0.24	0.05	0.01	0.38	0.4	0	0	0.08	3.1	0.85	0.1	0.04	0.07	0.02	0.05	0.03	0.1	0.1	0.07	0.03	0.03	1.49	51.9
Occurrence of fault at the end of PR lines	PAD	PR	0.69	0.43	0.8	0.64	0.74	0.93	0.93	0.74	0.64	0.8	0.43	0.69	8.45	0.47	0.38	0.51	0.41	0.52	0.47	0.47	0.52	0.41	0.51	0.38	0.47	5.49	35.0
		BR	1.39	3.62	2.05	2.85	2.03	1.54	1.54	2.03	2.85	2.05	3.62	1.39	26.95	1.23	2.35	1.38	1.43	1.28	1.08	1.08	1.28	1.43	1.38	2.35	1.23	17.49	35.1
		DCTI	0.4	2.9	0.94	1.91	0.99	0.31	0.31	0.99	1.91	0.94	2.9	0.4	14.9	0.47	1.68	0.57	0.72	0.46	0.31	0.31	0.46	0.72	0.57	1.68	0.47	8.42	43.5
	DDG1	PR	0.69	1.27	1.04	0.62	0.87	0.96	1.11	0.76	0.73	0.84	0.49	0.73	10.1	0.72	1.13	0.66	0.61	0.62	0.57	0.6	0.58	0.52	0.55	0.44	0.52	7.5	25.7
		BR	1.73	2.36	1.75	2.81	2.56	1.58	1.83	2.13	3.63	2.17	5.12	3.4	31.07	1.54	2.31	1.84	1.68	1.61	1.21	1.32	1.4	1.96	1.52	3.62	3.02	23.02	25.9
		DCTI	0.75	0.78	0.42	1.89	1.39	0.33	0.42	1.08	2.59	1.03	4.32	2.37	17.37	0.51	0.89	0.89	0.77	0.69	0.34	0.42	0.52	1.14	0.67	2.88	2.2	11.92	31.4
	DDG2	PR	0.7	0.86	0.79	**1.46**	1.08	0.91	1.35	0.74	0.84	0.83	0.57	0.72	10.85	0.62	0.76	0.93	**0.91**	0.74	0.69	0.7	0.64	0.59	0.56	0.51	0.52	8.16	24.8
		BR	2.11	60.17	2.07	**2.11**	1.68	1.51	2.24	2.09	4.66	2.14	7.77	3.17	91.72	1.87	37.57	1.82	**1.59**	1.98	1.3	1.54	1.43	2.42	1.55	5.39	2.81	61.27	33.2
		DCTI	1.1	59.02	0.97	**0.35**	0.3	0.3	0.59	1.05	3.52	1.02	6.9	2.15	77.27	0.95	36.52	0.59	**0.38**	0.94	0.31	0.54	0.49	1.54	0.69	4.58	1.99	49.52	35.9
	DDG3	PR	0.72	0.57	0.83	**0.84**	0.74	1.35	0.91	1.08	1.46	0.79	0.86	0.7	10.85	0.55	0.51	0.63	**0.59**	0.78	0.69	0.94	0.75	0.91	0.65	0.76	0.56	8.31	23.4
		BR	3.17	7.77	2.14	**4.66**	2.09	2.24	1.51	1.68	2.11	2.07	60.17	2.11	91.72	2.81	5.39	1.63	**2.39**	1.58	1.55	1.6	1.38	2.18	1.64	37.58	1.87	61.59	32.8
		DCTI	2.15	6.9	1.02	**3.52**	1.05	0.59	0.3	0.3	0.35	0.97	59.02	1.1	77.27	1.96	4.58	0.7	**1.5**	0.5	0.56	0.36	0.34	0.97	0.69	36.52	1.01	49.69	35.7
	DDG4	PR	0.73	0.49	0.84	0.73	0.76	1.11	0.96	0.87	0.62	1.04	1.27	0.69	10.1	0.53	0.44	0.58	0.52	0.63	0.58	0.65	0.62	0.61	0.65	1.13	0.61	7.54	25.3
		BR	3.4	5.12	2.17	3.63	2.13	1.83	1.58	2.56	2.81	1.75	2.36	1.73	31.07	3.02	3.62	1.56	1.9	1.47	1.3	1.33	1.61	1.92	1.56	2.31	1.54	23.12	25.6
		DCTI	2.37	4.32	1.03	2.59	1.08	0.42	0.33	1.39	1.89	0.42	0.78	0.75	17.37	2.19	2.88	0.69	1.08	0.53	0.42	0.37	0.7	1.01	0.6	0.89	0.63	11.99	31.0

Presence of all DGs: PAD Disconnection of DGi: DDGi Primary relay: PR Backup relay: BR Comparison of total DCTI: CTDCTI

According to the results of

Table **VIII**, it can be concluded that the DCTI in all relay pairs for the base case and all other structures with disconnected DGs is positive for both conventional and proposed characteristics and the coordination is preserved. However, the use of the proposed characteristic leads to a shorter OT for both primary and backup relays in the event of a fault somewhere in the line.

According to results, if the conventional characteristic is used, the OTs of the relays R4 and R6, for a fault at the beginning of the line DL-2 and in the absence of DG2 are 0.64 and 0.94 s, respectively. If the proposed characteristic is used, these times are reduced, respectively, to 0.40 and 0.71 s, i.e., by 37.5% and 24.47%, respectively. Moreover, for a fault at the beginning of the line DL-2 and in the absence of DG3, the OTs of these relays with the conventional characteristic are 0.37 and 1.40 s, respectively. However, if the proposed characteristic is used, these times are reduced, respectively, to 0.26 and 0.72 s, which show, respectively, 29.73% and 48.57% reduction.

The values in the last column of Table VIII (CTDCTI), which indicate the improvement in the total OT of the primary relays, the total OT of the backup relays and the total DCTI of relay pairs, are in percentage. Based on these results, it can be observed that, in all cases, the operating speed of the relays is increased. The maximum improvement in OTs of the primary relays, backup relays and DCTIs are 36.1%, 34.9% and 100%, respectively; these values correspond to a fault occurrence next to the primary relay in the base structure (presence of all sources). The minimum improvement in OTs of the primary relays, backup relays and DCTIs are 24.4%, 23.4% and 46.6%, respectively; these values correspond to a fault occurrence immediately next to the primary relay in case of the disconnection of DG3.

In the event of a fault at the end of the primary relay line, the minimum improvement in the relay operating speed occurs when DG3 is disconnected; the improvements in the OTs of primary relays, backup relays and DCTIs are only 23.4%, 32.8% and 35.7%, respectively. Accordingly, it can be concluded that the most critical structure in the ring configuration corresponds to the disconnection of DG3.

9. Conclusion

The approach to maintaining the OCRs coordination when the network structure changes (e.g., when DG units are disconnected) is to consider the coordination constraints of relay pairs in all structures. Additionally, by increasing the constraints of the CP, the solution space is limited and the relay OT increases. In this paper, a new characteristic consisting of current and impedance functions was presented. The current function was exactly the same as the conventional characteristic for OCRs. The impedance function was an exponential function in terms of the EI seen by the relay. It was found that in the event of the disconnection of DGs, changes in impedance compensate the changes in the fault current and lead to an improved coordination of relay pairs in different structures. Based on the simulation results, it is observed that in all structures of the connection or disconnection of the sources in both radial and ring configurations of the microgrid under study, the values of DCTI index are positive and the relay pairs coordination is maintained in all situations. Another advantage of the proposed characteristic is the increase in the speed of primary and backup protection. For example, in the base structure in which the network operates most of the time, the total DCTI of the relay pairs in the conventional method is 1.8 seconds. However, in the proposed adaptive method it is equal to 0 and a 100% improvement is achieved. This means that the OT of the relay pair is the fastest with no delay in the proposed method. Moreover, in the structures with the disconnection of DG1, DG2, DG3 and DG4, improvements in the protection system speed are, respectively, 51.3%, 47.8%, 46.7% and 51.9%. The average total OTs of the primary and backup protections in ring configuration decrease by 34.58. Therefore, according to the analytical relationships and simulation results, maintaining the coordination and improving the performance of overcurrent relays in different structures with DG sources can be achieved by the proposed adaptive characteristic using only the information at the relay location.

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