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Research Paper

Optimal Adjustment of Dualsetting Overcurrent Relays in Inverter-Based Microgrids

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Abstract: Increasing the penetration of distributed generation (DG) systems in power systems has many advantages, but it also has problems, including interference with the proper functioning of the protection systems. This problem is severe in microgrid systems that contain many DGs. Overcurrent relays are one of the most critical protection equipment of protection systems. The DG sources significantly change the characteristics of fault currents and the protection designs as well as the coordination of overcurrent relays. This paper proposes a coordination method for directional overcurrent relays with dual adjustment to resolve the interference problem in the protection system of a microgrid in the presence of distributed generation sources based on the electronic power converter (inverter). This is done by considering the curve of different standard characteristics according to the IEC60255 standard in two operating modes, the grid-connected and islanded. A genetic optimization algorithm is used to reduce the total operating time of the relays. The simulation results verify the effectiveness of the proposed coordination method. The results show that the protection coordination scheme with dual adjustment relays and the use of combined characteristic curves can significantly reduce the operating time of the total relays.

Keywords: Microgrid Protection, Dual Adjustment Directional Overcurrent Relays, Inverter-based Microgrids, Standard Characteristic Curve.

1 Introduction

INCREASING the penetration of distributed generations (DGs) in distribution networks has many benefits, such as increasing system efficiency and quality in supplying electricity to customers, reducing losses, increasing reliability, and reducing environmental pollution [1]. Studies show that DG will play an essential role in meeting future electricity needs [2], [3]. These advantages come into play when the disadvantages of these resources on distribution networks are carefully analyzed and examined. For example, using DGs can cause problems in protection systems, reduce reliability and power quality, and complicate controlling and operating the power grids. The microgrid is a new concept presented for more efficient and economical use of DG sources and solving the problems of these units in the distribution system [4], [5].

Protection problems are the most critical issues in microgrids [6]. In the microgrid protection system, overcurrent relays are commonly used, and their miscoordination operation causes the protection system to malfunction. In a microgrid protection system, there is usually a backup relay for each main

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relay. The subject of coordination of overcurrent relays is to determine the time setting coefficient and current setting coefficient. In normal operation, there is no interference in the operation of the main and backup relays and only the main relay operates and the fault disconnects from the main grid in the shortest time. In other words, miscoordination in overcurrent relays is one of the adverse effects of the entry of distributed generation sources into the distribution network. This coordination problem is due to a change in the size and direction of the power flow through the system consequence of unusual conditions or short-circuits in the network. The magnitude of the impact of the distributed generation source on power flow depends on the position, size, and structure of DG [7], [8].

Several studies in the literature have reported issues related to coordination and protection in microgrids [9], [10]. Minimizing the operating time of the protection system and solving the problem of coordination of overcurrent relays and formulations the problem is the main subjects in this area of research. For example, in [11] for meshed networks, it is suggested to start the coordination from the point of fault and inconsistency for both possible directions. The aim of reference [12] is to study directional overcurrent relays (DOCRs) coordination considering the effects of the different network topologies in the optimization problem based on a new genetic algorithm (GA) hybrid method. The use of intelligent methods to solve the problem of optimization and coordination has been considered in [13]. The value of the objective function in these problems is considered to minimize the possible operating time for the overcurrent relays. The objective function can be formulated using the nonlinear programming (NLP) method, and in some cases, the objective function is presented in the form of linear programming (LP). In recent years, innovative methods, such as genetic algorithms, particle swarm optimization (PSO), and others have been proposed to address the important issue of overcurrent relay coordination, as reported in references [14] and [15].

The DG sources are divided into two general categories: synchronous generator (SG) and inverter-based distributed generation (IBDG) in terms of performance and network connection. The DG sources in the microgrid are typically renewable energies. These sets are usually connected to the power network but can be automatically separated from the network for physical and economic reasons. One of the major protection problems that can cause the protection system to malfunction is the limited fault current of the IBDG sources. This fault current is about 1.1 to 2 times of rated relay current of the inverter, while the synchronous distributed generation sources have a significant fault current [16], [17]. The low fault current of IBDG often causes the overcurrent relays to malfunction in fault detection during short-circuit currents [18].

The issue of overcurrent relay coordination is an optimization problem with a significant number of constraints. The main goal of addressing the overcurrent relay coordination problem is to minimize the operating time of relays for faults occurring within both the main and backup relay protection zones [19]. According to research on the coordination problem in recent years, some challenges have been reported, such as achieving the minimum operating time of relays and developing a protection plan with proper features including fast response, reasonable cost, sensitivity, and detectability. Using one of the above features alone will lead to coordination, which may not achieve the other feature [20]- [22]. Therefore, to implement a suitable protection system, it is always necessary to use methods that include the most features of a desirable protection design, and the optimal value of the objective function is calculated by reducing the maximum number of miscoordinations.

In this paper, the operating time of the total relay is reduced by using the two concepts of dual-setting directional overcurrent relay coordination and considering different standard characteristic curves. A modified objective function is used for the overcurrent relay coordination problem to reduce the number of miscoordinations. In summary, the innovation of this thesis lies in the utilization of two concepts: dual adjustable directional overcurrent relays and different standard characteristic curves as per the mentioned standards. Additionally, the objective function formula has been modified using a penalty function, which provides an optimal solution to the coordination problem without any inconsistencies. This leads to better control over the main relays and their backup, resulting in improved time management and performance of the relays.

In the rest of this paper, Section 2 introduces the challenges of microgrid protection. Section 3 describes the principles of overcurrent relay coordination. In Section 4, simulations are performed, and the results are discussed. Section 5 concludes the paper and highlights the main contributions.

2 Challenges of microgrid protection

Connecting the distributed generation sources to a distribution network causes local changes in network characteristics. Connecting a generator (or a distributed generation source) to a distribution network increases the level of fault in the network close to the connection point. In other words, this connection increases the short-circuit current level of the network. Increasing the fault level can cause hazards and adverse effects; it can also damage the network and cause malfunction and power outages. So, when connecting a generator to the power grid, it is essential to calculate the fault current and make appropriate changes to the protection coordination and other system protection settings. This will help ensure that the system is adequately protected against any potential issues that may arise due to the new connection [23].

The United States Department of Energy defines microgrids as: "Microgrid is a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both connected or island mode" [24]. Although microgrids have some merit benefits, there are some challenges in using these systems due to many technical challenges, such as protection, power quality, security, islanded and grid-connected operating modes, voltage and frequency control, energy management, and system stability [25]. Among these issues, a critical factor in microgrid development is the protection issue, especially in the presence of distributed generation sources. In addition to the benefits of integrating distributed generation sources with associated systems, these resources may also have significant delays in the operation, control, and protection systems. In the distribution network, conventional protections are programmed based on the radial systems of the distribution networks. However, if distributed generation sources are connected to the system, in some places, the feeders become bidirectional, and current may flow in both directions, so these feeders are not considered radial.

2.1 Two-way power flow

As mentioned above, in microgrids, the network configuration is not redialled due to the presence of distributed generation sources, so the power flow is different from the usual distribution network. The presence of multiple sources in the network may cause two-way power flow, so in distribution networks, the performance of overcurrent protection devices and equipment may be affected [26].

2.2 Effect of operation modes on protection system

Connecting and disconnecting distributed generation sources causes another challenge due to successive microgrid configuration changes, resulting in fault current changes. Also, when the microgrid changes from an islanded mode to a grid-connected or vice versa, its configuration will be affected. Therefore, short-circuit currents will cause changes in a wide range. Designing an appropriate and effective method for protecting microgrids is essential for two key reasons. One of these is that microgrids must be dynamic networks; in fact, a load or a distributed generation unit must be able to connect or disconnect to a microgrid at any given time. Another reason is that microgrids must operate with different short-circuit currents, both in the islanded and grid-connected operating modes. Therefore, a comprehensive design should include the ability to protect the microgrid in both modes [27].

In grid-connected mode, the power flow is much higher than in islanded mode. For this reason, in the grid-connected operating mode, the fault current level is at a higher level. The fault current level in the microgrid is significantly reduced after switching to islanded mode. This fault current differentiation causes the overcurrent relays to malfunction. When the protection system is set to high fault values considering the grid-connected mode, it may not detect the fault when switching to islanded mode, so it can have a sudden voltage drop. When the protection system is set to fault values according to the islanded mode, after switching to the grid-connected mode, it causes interruption and wrong operation [28].

2.3 Limited fault current of inverter-based distributed generation sources

Under normal conditions, the distributed generation sources inject electrical power via electronic power converters into the network. During a network fault, the converter controller needs to respond to the disturbance and minimize any negative impact on the network. Due to the low thermal capacity of inverters, the current passing through them must be limited even on very short time scales. If the current passing through them exceeds the tolerable values, the semiconductor switches will be damaged. Therefore, the inverter overheating should be prevented by limiting the inductor current. This current is usually limited to a maximum of two times the rated current. As a result, designing appropriate control and protection methods is especially important to allow the inverter to transition between normal mode and fault mode, and to return to normal mode. In other words, the methods used must operate in such a way as to ensure that the inverter current does not exceed the permissible limits [29].

As mentioned above, the output current of the inverter-based sources is usually limited by its control system during the fault. This limited fault current of the inverter can lead to the malfunction of the protection system, especially in the system mostly based on overcurrent relays. Therefore, inverter sources must have internal protection to ensure the safety of semiconductor devices against large fault currents. The impact of this internal protection must be taken into account when protecting the entire network, as the inverter's internal protection is unable to detect fault currents that are smaller than its setting. In inverter-based microgrids, fault detection and operation of protection systems after fault clearing debugging are more complex due to the unique characteristics of inverter sources, as well as the various configurations and control systems utilized. [30].

3 Principles of coordination of overcurrent relays

Among the protection methods, overcurrent relays are very common due to their cheapness and simplicity. These relays are used both as main protection and backup protection. The operating time (t_{ij}) of an overcurrent relay is inversely related to its short-circuit current [31]. In general, the operating time of an overcurrent relay is expressed as (1):

$$t_{ij} = \frac{A \, . \, TDS}{\left(\frac{I_{fi}}{I_{pi} \, .CTR}\right)^{B} - 1} \tag{1}$$

The parameter i and j represents the relay number and the fault location, respectively. The constants A and B are the type curves of the inverse time relay characteristic curve based on the IEC60255 standard, as shown in Table 1. I_{fi} indicates the short-circuit current of the relay, I_{pi} indicates the current setting coefficient of the relay, and TDS indicates the time setting of the coefficient of the relay. The current transformer ratio (CTR) is also defined for each relay.

Table 1 Reverse time characteristic curve constants.

Relay characteristics curve	A	B
Simple Inverse (SI)	0.14	0.02
Very Inverse (VI)	13.5	1
Extremely Inverse (EI)	80	2

3.1 Conventional directional overcurrent relays and dual adjustment

In the reverse time characteristic, the relay operating time decreases with increasing fault (current) rate to prevent damage to the equipment [32]. Based on this characteristic, the relays can be categorized into three types: simple inverse (standard inverse), very inverse, and extremely inverse, as shown in Figure 1.

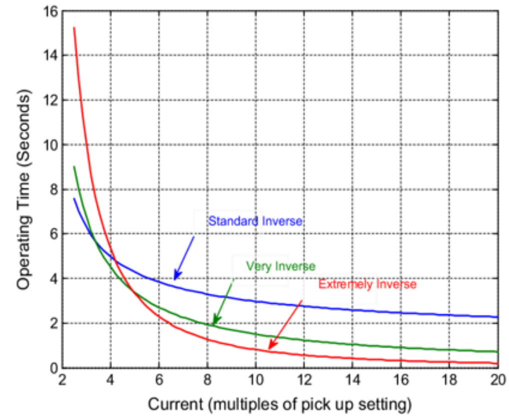


Fig. 1 Types of overcurrent relays, reverse time.

The DOCR, in addition to measuring current, also detects the direction of current flow. In this type of relay, voltage and current signals are used to detect the direction of the current direction. Directional overcurrent relays use the same reverse time characteristic of overcurrent relays, as shown in Figure 2. These relays operate if the direction of the passing current is the same as the direction of the relay.

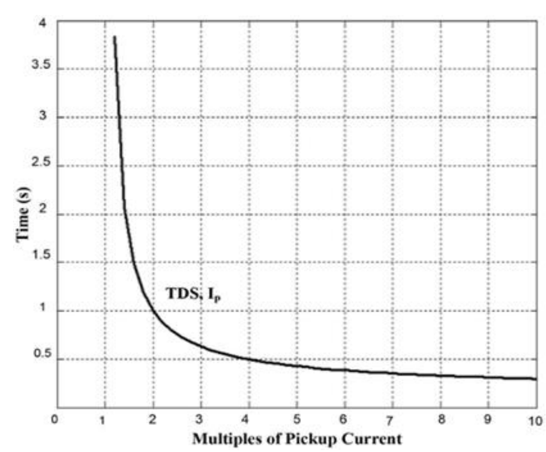


Fig. 2 Conventional time-current characteristic of DOCR.

Figure 3 shows an example of a 3-bus meshed system with six DOCRs. If a fault occurs at point A, R1 will be the main relay, and in case of a failure, R5 will act as its backup.

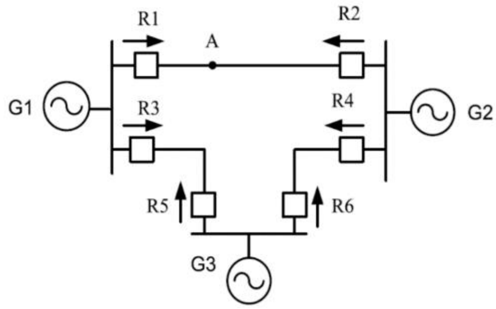


Fig. 3 Protection with conventional directional overcurrent relays.

Utilizing dual adjustable directional relays in a protection coordination scheme offers advantages in terms of flexibility and operational capabilities. These relays are designed to operate in both forward and inverse directions for faults, with two distinct relay characteristics that correspond to each direction. Figure 4 shows the time-current characteristic of the dual adjustment directional overcurrent relay [33].

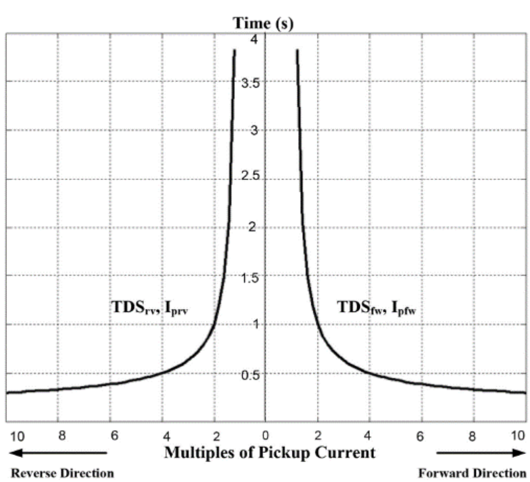


Fig. 4 DOCR time-current characteristic of dual adjustment.

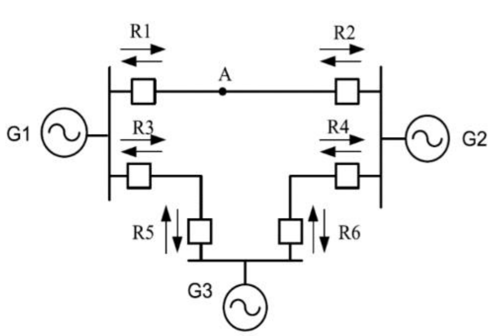


Fig. 5 Protection with dual adjustment directional overcurrent relays.

The relay acts as the main protection when the fault current is in the forward direction and as backup protection for a fault current in the inverse direction. The relay will have two different settings; main protection (forward) and backup protection function (inverse). Figure 5 shows an example of a 3-bus meshed system with six DOCR dual adjustments. Each relay has two arrows that indicate the two directions of the fault current that the relay can operate. For a fault at point A in Figure 5, R3 will be the backup relay for R1 while R4 will be the backup relay for R2. In such cases, R3 will use the inverse function settings, while R1 will use the forward function settings.

The primary protection of the DOCR is in the forward direction, and it can be adjusted to achieve the shortest operating time. Moreover, the operating time of the backup protection will also be reduced due to the reduction of the main operating time. In fact, with the use of dual-setting relays, each relay's main protection and the backup protection role are divided into two different settings. So, the dependency between settings decreases and the relay settings become independent of each other, which leads to a significant reduction in the operating time of the relays [34]. The operating time (top) of a directional overcurrent relay with dual adjustment for forward and inverse directions is shown in (2) and (3), respectively:

$$t_{\mathrm{op,fow,ij}} = \frac{A\ .\ TDS(fow,i)}{\left(\frac{If(fow,i)}{Ip(fow,i)\ .\ CTRi}\right)^{B} - 1} \tag{2}$$

$$t_{\mathrm{op,rev,kj}} = \frac{A\ .\ TDS(rev,k)}{\left(\frac{If(rev,k)}{Ip(rev,k)\ .\ CTRk}\right)^{B} - 1} \tag{3}$$

where parameters *i* and *k* represent the relay, and *j* represents the fault location; $t_{op,fow,ij}$ and $t_{op,rev,kj}$ represent the operating times of relays *i* and *k* for a fault at location *j*, respectively, during the main and backup operation. *TDS(fow,i)* and *TDS(rev,k)* show the time settings of relay *i* and *k*, respectively, in the forward and inverse directions. *Ip(fow,i)* and *Ip(rev,k)* are the current settings of the relay *i* and *k* in the forward and inverse direction of a fault in position *j*, respectively.

The main purpose of solving the coordination problem is to minimize the total operating time of the relays. For directional overcurrent relays with dual adjustment, the objective function (OF) is defined as (4):

$$\mathrm{OF}=\min \sum_{\mathrm{j}=1}^{M} \left(\sum_{\mathrm{i}=1}^{N} \mathrm{top(fow,ij)} + \sum_{\mathrm{k}=1}^{N} \mathrm{top\ (rev,kj)} \right) \tag{4}$$

where M and N represent the number of fault locations and the number of relays in the feeders, respectively. Each dual-setting overcurrent relay has two settings for both the main and backup functions. The main purpose of optimization is to minimize the total operating times of all relays (main and backup) while achieving protection coordination conditions [35].

Among two overcurrent relays, one is defined as the main relay *(fow,i)* and the other as the backup relay *(rev,k)*. Therefore, to coordinate between two relays in a microgrid, for a short-circuit at the location of the main relay, the operating time of the backup relay must be greater than the operating time of the main relay as much as the coordination time interval (CTI). This constraint can be expressed as follows:

$$t_{rev,kj} - t_{fow,ij} \geq CTI \quad \forall\ i, j, k \tag{5}$$

For example, if the main and backup relays have a dual setting characteristic, then the inequality (5) can be expressed as (6):

$$\frac{A\ .\ TDS(rev,k)}{\left(\frac{If(rev,k)}{Ip(rev,k)\ .\ CTRk}\right)^{B} - 1} - \frac{A\ .\ TDS(fow,i)}{\left(\frac{If(fow,i)}{Ip(fow,i)\ .\ CTRi}\right)^{B} - 1} \geq CTI \tag{6}$$

For optimal coordination of power system relays, for each fault, the operating time of the backup relays should be CTI time larger than the time of the main relays. CTI typically takes values between 0.2 and 0.5 seconds, and in this paper, a value of 0.2 seconds is selected. Relationships (7)- (10) show the limits and constraints under consideration on the relay configuration parameters.

$$Ip_{i\text{ - }min} \leq Ip(fow,i)\ \&\ Ip(rev,i) \leq Ip_{i-max} \tag{7}$$

$$TDS_{i-min} \leq TDS(fow,i)\ \&\ TDS(rev,i) \leq TDS_{i-max} \tag{8}$$

$$Top_{i-min} \leq Top(fow,i)\ \&\ Top(rev,i) \leq Top_{i-max} \tag{9}$$

$$1 \leq CC \leq 3 \tag{10}$$

where *Ipi-min* and *Ipi-max* show the upper and lower bounds of the current settings for relay *i*. *TDSi-min* and *TDSi-max* parameters are the upper and lower bounds of the time settings for relay *i*. *Topi-min* and *Topi-max* are the upper and lower bounds of the operating time for relay *i*. The equations are valid for the relay *k*.

In this paper, the lower and the upper limit of the relay operating time are considered to be 0.1 and 2.5 seconds, respectively. Characteristic curve (CC), indicates the type of standard characteristic curve. Using different characteristic curves means that, by having the values of the coefficients of the characteristic relay curve (A, B) as two decision variables, it is possible to create more flexibility than the problem of relay coordination. Therefore, to achieve the desired coordination of microgrid relay protection, it is necessary to select the optimal characteristic curve and relay settings.

Each relay is associated with six setting indices, three settings in the forward direction and three settings in the inverse direction, which determine the operating time of the relays. The indices consist of time dial setting (TDS), current setting (I pick-up [A]), and characteristic curve type (CC).

3.2 Objective function

Various optimization methods have been suggested to address the issue of coordinating overcurrent relays [36]. Achieving optimal settings for all system relays is the main goal of most of these methods. Depending on the speed and selectivity of a protection system, overcurrent relays must be adjusted to minimize operating time. The problem of relay coordination is defined as an optimization problem with some constraints. The main purpose of the overcurrent relay coordination problem is to minimize the operating time of the overcurrent relays for faults within the main and backup relay protection zone.

With the penetration of inverter-based distributed generation sources in power systems, it becomes difficult to adjust the coordination of the overcurrent relays. The objective function used is to minimize the total operating time of directional overcurrent relays with dual adjustment. The modified objective function aims to quantify the occurrences of miscoordination as well as the instances where it is not present during optimization. This approach provides greater control over the primary and backup relays, as well as the management of performance time.

With DOCR, the optimization aims to achieve optimal coordination of directional overcurrent relays with dual adjustment. Duo to this aim, in this paper, an objective function with a penalty term is defined as below.

$$OF = \min \sum_{J=1}^{M} \left(\sum_{i=1}^{N} top\ (fow,ij) + \sum_{k=1}^{N} top\ (rev,kj) \right) + \alpha\ (ttc+tmc) \tag{11}$$

where N is the sum of all possible relays, and M is the sum of the potential fault locations. The expression *α(ttc+tmc)* is considered a penalty term, *ttc* is the number of relays miscoordinations whose operating time is not between 0.1 and 2.5 seconds; *tmc* is the number of relays miscoordinations that are not observed in the coordination time interval (CTI).

The objective of function (11) is to reduce the number of relays and the overall operating time of the relays. The penalty term ($\alpha(ttc+tmc)$) is added to the objective function to consider the constraint of zero miscoordinations. In the presence of miscoordinations, the penalty function radically increases, resulting in the objective function not being an optimal answer. The coefficient α is considered a large value. Therefore, the optimal solution is calculated when the number of miscoordinations and consequently the penalty function is zero, where the boundaries are satisfied.

It is worth mentioning, that in (11) the objective function aims to calculate the operating time of the relays for all considered faults; however, this question may arise, is it better to use an objective function should calculate the operating time of the primary (main) and the backup operating time for the corresponding relays for each fault location? There could be several reasons why some power system relay setting authorities have chosen to optimize the total time of the relays in the sub-system, rather than obtaining the optimal time for the operation of a relay and its backup.

One reason could be that it is simpler to optimize the total time of the relays in the sub-system, as it requires a less detailed analysis of the individual relays and their characteristics. This approach may be more appropriate for smaller or less complex power systems, where the coordination requirements are relatively straightforward.

Another reason could be that the authorities may not have access to sufficient information or data to accurately determine the optimal settings for each individual relay and its backup. In such cases, it may be more practical to use a simplified approach that takes into account the total response time of the relays in the sub-system.

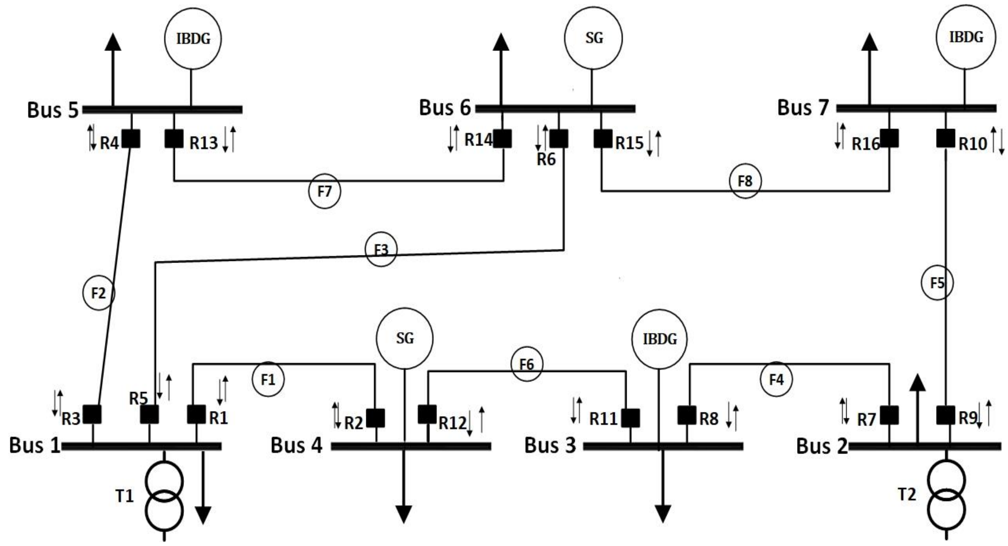
Additionally, some authorities may choose to optimize the total time of the relays in the sub-system to ensure that the overall system stability and reliability are maintained, even if it means sacrificing some level of coordination between the individual relays. This approach may be appropriate in situations where the consequences of a failure or disruption in the power system are severe.

However, it is important to note that optimizing the total time of the relays in the sub-system may not always result in optimal coordination and performance, particularly in larger or more complex power systems. In such cases, it may be necessary to conduct a more detailed analysis to determine the optimal settings for each individual relay and its backup, to ensure the highest level of reliability and performance.

4 Simulation Results

The proposed protection scheme is applied to a 7-bus system microgrid, which is derived from an IEEE 14-bus system, with 16 dual adjustments directional overcurrent relays, in two islanded and grid-connected operation modes. Fig. 6 shows the microgrid understudy, with three inverter-based distributed generation sources (IBDG) connected to buses 3, 5, and 7. All overcurrent relays have reverse time characteristics. The eight points marked in the middle of the lines are short circuit points (F1- F8). Due to the grid configuration, each fault is protected by two main relays. Because of the configuration, the number of backup relays for some faults may be more than two.

The system under study in Figure 6 with the proposed optimal adjustment method for the directional overcurrent relays is simulated. The load-flow and short-circuit calculations are simulated offline in the DIGSILENT environment. The flowchart shown in Figure 7, illustrates the process of optimal coordination of relays.



SG: Synchronous Generator, IBDG: Inverter-Based Distributed Generation
Fig. 6 7-bus system with dual adjustment specifications for directional overcurrent relay (part of IEEE 14-bus network).

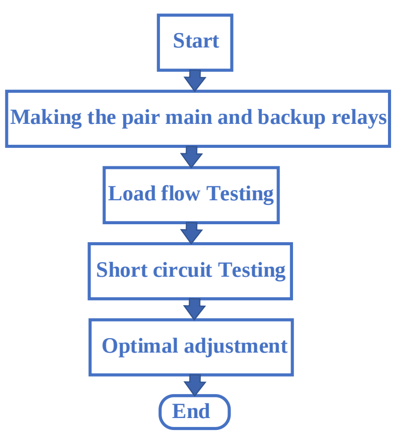


Fig. 7 Process of optimal coordination of relays

4.1 Optimal coordination of relays using genetic algorithm

To optimize the coordination of relays, the genetic algorithm is used in the MATLAB software environment. In the genetic algorithm, each chromosome consists of 96 initial elements. The first 16 elements determine the current setting in the forward direction, the next 16 elements determine the characteristic curve type in the forward direction, the next 16 elements determine the relay setting time in the forward direction, the following 16 elements determine the current setting in the reverse direction, the next 16 elements determine the characteristic curve type in the reverse direction, and the final 16 elements determine the relay setting time in the reverse direction. The chromosome used for relay settings is shown in Figure 8. In the implemented code, the initial population size is 500 and the genetic algorithm is repeated 200 times. The probability of crossover (PC) and probability of mutation (PM) are set to 0.8 and 0.2, respectively. Table 2 shows the most important parameters adjusted for the genetic algorithm.

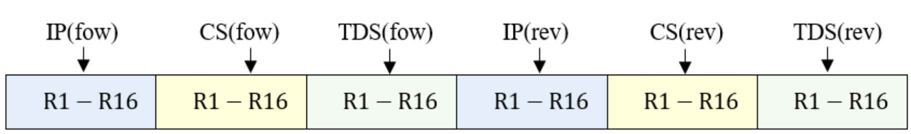


Fig 8 The chromosome used for relay settings in genetic optimization

Table 2 Parameters of the genetic algorithm

Parameter	Value
Probability of crossover (PC)	80%
Probability of mutation (PM)	20%
Number of the initial population	500
Number of GA repetition	200

Table 3 Optimal adjustment of directional overcurrent relays with combined characteristic curves EI, VI, SI with dual and conventional DOCR adjustment in microgrid with islanded mode.

Relay	**Relay with combined characteristic curve EI, VI, SI according to IEC-60255 Std**								
	Conventional adjustment DOCR			**Dual-setting DOCR**					
	TDS [S]	**IP [A]**	**CC**	**TDS(S) Forward**	**IP [A] Forward**	**CC Forward**	**TDS[S] Reverse**	**IP [A] Reverse**	**CC Reverse**
R1	0.3243	1.5	SI	1.9959	1.0	EI	0.0861	1.7	SI
R2	1.1851	1.2	VI	0.2386	1.0	VI	0.1020	1.4	SI
R3	0.9615	1.0	EI	2.0454	1.0	EI	0.0623	1.0	SI
R4	2.3587	0.8	VI	0.1760	1.2	VI	1.3112	1.8	EI
R5	0.2184	1.5	SI	2.0462	1.2	EI	0.0971	1.0	SI
R6	0.3284	0.5	VI	0.1824	1.2	SI	0.2248	1.0	VI
R7	1.2054	0.9	EI	0.1786	1.3	VI	0.1535	1.6	EI
R8	1.2917	1.6	VI	0.1798	1.0	SI	0.1461	1.0	SI
R9	1.3052	1.0	VI	0.1992	2.1	EI	0.1744	1.0	EI
R10	0.6016	0.5	EI	0.1847	1.0	EI	0.1852	1.7	EI
R11	2.1541	0.7	VI	0.1976	1.5	VI	0.1475	1.8	SI
R12	0.7585	1.2	EI	1.9967	1.7	SI	0.1481	2.2	VI
R13	0.2667	0.5	SI	2.3340	2.0	EI	0.2173	1.0	SI
R14	0.6031	1.5	VI	1.4411	1.0	SI	0.1582	1.3	VI
R15	0.2951	1.1	SI	0.1778	1.4	VI	0.6116	1.0	EI
R16	0.7318	1.0	EI	0.1911	1.3	VI	0.3862	1.0	VI
Top	**17.1482 sec**			**9.0024 sec**					

4.2 Optimal adjustment for microgrids in islanded mode

The optimal settings obtained for the 7-bus system are provided using different relay characteristic curves (according to the IEC60255 standard) for a microgrid in islanded mode, using 16 directional overcurrent relays, in two modes of conventional adjustment and dual adjustment. The optimal settings with standard characteristic curves of SI, VI, and EI are compared with the dual and conventional adjustment of directional overcurrent relays (DOCR), as shown in Table 3. By taking into account the overall operating time of the relays and the value of the objective function, the operating time of the relays is substantially decreased when using the dual setting mode.

Figure 9 illustrates the DOCR operating time diagrams with conventional and dual settings with different characteristic curves in the microgrid with islanded mode; based on this figure, a comparison of the decrease in time between conventional and dual settings with different characteristic curves is shown in Table 4. According to these results, the operating time of dual adjustable directional overcurrent relays with standard characteristic curves SI, VI, and EI, as well as the combined mode of standard characteristic curves, are reduced in comparison with directional overcurrent relays with conventional adjustment. In addition, the combined mode of the standard characteristic curve for dual adjustment directional overcurrent relays shows better operating time than the use of them with the conventional setting and is the best option to achieve the objective function is considered to be the coordination problem in inverter-based microgrids.

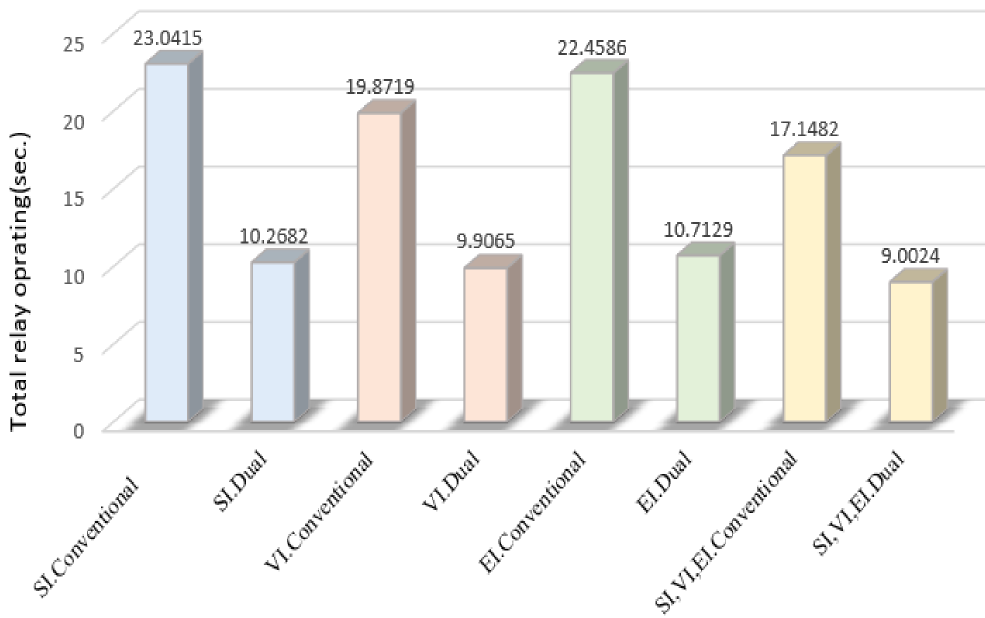


Fig. 9 DOCR operating time diagrams with conventional and dual settings with different characteristic curves in an islanded microgrid.

Table 4 Comparison of decrease in time between conventional and dual settings with different characteristic curves in an islanded microgrid.

Characteristic curves	**SI**	**VI**	**EI**	**Combined mode**
Decrease in time	55.43%	50.14%	52.29%	47.5%

Figure 10 shows the decreasing trend of the objective function in the genetic algorithm for DOCR dual-regulated with the combined mode of standard characteristic curves in an islanded mode.

As can be seen from Figure 10, the genetic algorithm has converged well to the optimal solution. However, it is worth mentioning, that a genetic algorithm for such a problem that consists of both discrete and continuous parts may face convergence problems. To mitigate convergence problems, several techniques can be used. One approach is to use a diversity maintenance mechanism, such as crowding or niching, to encourage the population to maintain diversity. Another approach is to introduce randomness into the algorithm, such as through mutation or crossover, to explore the solution space. Additionally, the parameters of the algorithm, such as the population size, crossover rate, and mutation rate, can be adjusted to balance exploration and exploitation.

4.3 Optimal adjustment for microgrids in grid-connected mode

The optimal settings obtained for the 7-bus system using different characteristic relay curves (according to the IEC60255 standard) for microgrids in grid-connected mode, using 16 directional overcurrent relays, in both conventional and dual settings modes, are provided. Optimal settings of directional overcurrent relays with standard characteristic curves of SI, VI, and EI are compared with the dual and conventional adjustment of directional overcurrent relays (DOCR) in the microgrid with grid-connected mode, as shown in Table 5.

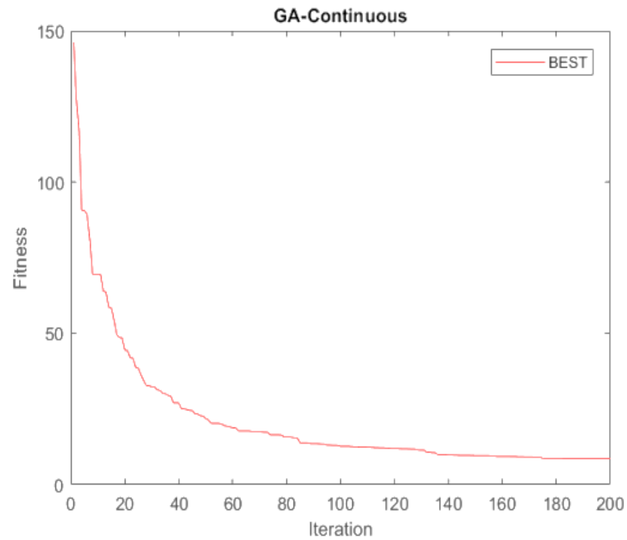


Fig. 10 The decreasing trend of the objective function with the genetic algorithm for islanding mode.

Table 5 Optimal adjustment of directional overcurrent relays with combined characteristic curves of EI, VI, and SI with dual and conventional DOCR adjustment in microgrid with grid-connected mode.

Relay	**Relay with combined characteristic curve EI, VI, SI according to IEC-60255 Std**								
	Conventional adjustment DOCR			**Dual-setting DOCR**					
	TDS [S]	**IP [A]**	**CC**	**TDS[S] Forward**	**IP[A] Forward**	**CC Forward**	**TDS[S] Reverse**	**IP[A] Reverse**	**CC Reverse**
R1	0.1258	1.4	VI	0.0673	1.4	EI	0.3989	1.0	EI
R2	0.1289	1.0	EI	0.0721	1.2	EI	0.4229	1.1	EI
R3	0.0862	1.0	VI	0.0810	1.2	VI	0.0585	1.0	VI
R4	0.0829	1.7	VI	0.0859	1.3	EI	0.5433	2.4	EI
R5	0.1142	1.4	SI	0.1054	1.2	EI	0.0836	1.0	EI
R6	0.0890	1.2	EI	0.0754	1.5	SI	0.3913	1.0	SI
R7	0.0873	1.5	SI	0.0875	1.0	VI	0.0841	1.2	EI
R8	0.1076	1.6	SI	0.0811	1.0	EI	0.4062	1.5	SI
R9	0.1182	1.2	EI	0.0794	1.0	VI	0.0893	1.1	VI
R10	0.0851	1.0	VI	0.0794	1.2	SI	0.4151	1.0	VI
R11	0.0840	2.5	EI	0.0500	1.3	EI	0.2590	2.4	EI
R12	0.1138	1.7	VI	0.0513	1.5	VI	0.3979	1.0	VI
R13	0.0674	2.5	EI	0.0796	1.0	VI	0.5647	2.1	VI
R14	0.2977	1.5	VI	0.0738	2.5	SI	0.0859	1.2	SI
R15	0.0826	2.5	SI	0.0729	1.0	EI	0.0763	1.1	VI
R16	0.0641	1.0	EI	0.0938	1.0	VI	0.4308	1.0	SI
Top	**15.5922 sec**			**7.3104 sec**					

Due to Table 5, the relay operating time in the dual-setting mode is greatly reduced. The characteristic curves used in this section are all randomly selected from the SI, VI, and EI characteristic curves for each of the relays by the genetic optimization algorithm.

According to Figure 11 and Table 6, the operating time of dual adjustable directional overcurrent relays with standard characteristic curves SI, VI, EI, and the combined mode of standard characteristic curves are reduced relative to the operating time of directional overcurrent relays with the conventional setting.

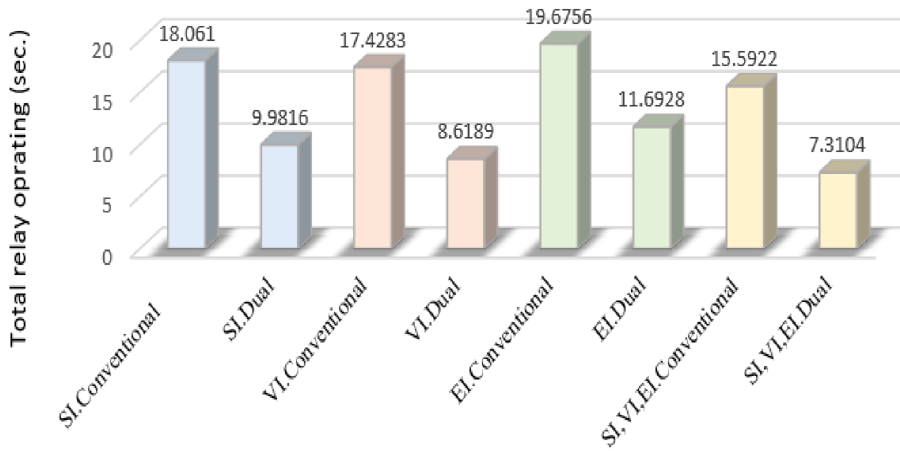


Fig.11 DOCR operating time diagrams with conventional and dual settings with different characteristic curves in the microgrid with grid-connected mode.

Table 6 Comparison of decrease in time between conventional and dual settings with different characteristic curves in the microgrid with grid-connected mode.

Characteristic curves	**SI**	**VI**	**EI**	**Combined mode**
Decrease in time	54.48%	50.54%	40.57%	53.11%

5 Conclusion

The coordination problem of the directional overcurrent relays in a microgrid with the distributed generation sources based on the electronic power converters is studied. The converters limit the fault output current to twice the rated current. With this limitation, the directional overcurrent relays may not operate correctly. The main goal of coordinating directional overcurrent relays is to minimize the relays operating time in the fault situations within the protection zone. For this goal, the dual setting directional overcurrent relays with different characteristic curves are employed, and an objective function (with penalty term) is defined to provide the optimal answer for the coordination problem with zero miscoordinations. When the proposed protection scheme is applied to a system being studied, the results show that the operating time of dual adjustable directional overcurrent relays with standard characteristic curves (SI, VI, EI) and the combined mode of standard characteristic curves is significantly reduced compared to the operating time of directional overcurrent relays with conventional settings. This is observed in both islanded and grid-connected modes. Among the different characteristic curves, the use of the combined curve shows a shorter operating time.

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