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Highly Fast Innovative Overcurrent Protection Scheme for Microgrid Using Metaheuristic Optimization Algorithms and Nonstandard Tripping Characteristics

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ABSTRACT The incorporation of renewable energy microgrids brings along several new protection coordination challenges due to the new and stochastic behaviour of power flow and fault currents distribution. An optimal coordination scheme is a potential solution to develop an efficient protection system to handle the microgrid protection challenges. In this paper, new optimal Over Current (OC) relays coordination schemes have been developed using nonstandard tripping characteristics for a power network connected to renewable energy resources. The International Electrotechnical Commission (IEC) microgrid and IEEE-9 bus systems have been used as benchmark networks to test and evaluate the coordination schemes. The proposed OC relays coordination approach delivers a fast and more reliable performance under different OC faults scenarios compared to traditional approaches. In addition, to improve and evaluate the performance of the proposed coordination approach, four modern and novel metaheuristic optimization algorithms are developed and employed to solve the OC relay coordination problem, namely: Modified Particle Swarm Optimization (MPSO), Teaching Learning (TL), Grey Wolf Optimizer (GWO) and Moth-Flame Optimization Algorithm (MFO). In this paper, the modern metaheuristic algorithms have been employed to handle the impact of renewable energy on the grid, and enhance the sensitivity and selectivity of the protection system. The test cases, consider the impact of integrating the different levels of renewable energy resources (with a capacity increment of 25% and 50%) in the microgrid on the OC relays protection performance by using nonstandard and standard tripping characteristics. In addition, a comparison analysis for the modern metaheuristic algorithms with Particle Swarm Optimization (PSO) algorithm as a common and standard technique in solving coordination problems under different fault scenarios considering also the higher impedance faults are introduced. The results in all cases showed that the proposed optimal nonstandard approach successfully reduced the overall tripping time and improve the performance of the protection system in terms of sensitivity and selectivity.

INDEX TERMS Over current relays, optimal coordination, distribution generation, nonstandard tripping characteristics.

I. INTRODUCTION

A. BACKGROUND

In traditional power networks, power is centrally generated and transferred to the end-users by using high, medium and low voltage networks with a unidirectional power flow. Nowadays, the rapid implementation of Distributed Generation (DG) such as renewable energy resources in modern power systems or microgrids has introduced a new trend of power generation and distribution schemes to achieve a more sustainable electrical grid and meet the yearly increase in electrical demand [1]. However, the incorporation of DGs

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into power networks brings along several new protections challenges due to the new behaviour of power flow and fault current distributions [2], [3]. The fact that microgrids and modern power networks with DGs are flexible systems, where changed the power system from radial into multi-looped systems under different operational modes.

The power protection system for a network equipped with DGs needs to handle two remarkable challenges: firstly, the dynamic behaviour of DGs with the bidirectional flow, and secondly the ability to operate the power network model as a utility grid-connected or islanded network model. These challenges create selectivity OC protection problems and increase the complexity of designing an optimal protection coordination scheme due to the bidirectional and variable short circuit currents (levels and direction) [2], [4]. Generally, the protection system needs to guarantee the stability and reliability of the network intermittent DG units and loads with the minimum possible operation time for the protection relays. Therefore, different techniques have been suggested and used in the literature to find the optimal coordination of Over Current Relay (OCR) setting in a microgrid [5]–[7]. However, the impact of increasing the capacity of DGs within a power network, type of faults, islanded modes and using nonstandard tripping characteristics on the protection coordination was not investigated and it is important to be introduced and studied. This article aims to introduce and evaluate the significance of designing new optimization approaches for reducing the overall protection times and guaranteeing selectivity by using nonstandard characteristics and novel optimization solvers. In addition, to enhance the real networks, this article shows the impact of integrating the different levels of renewable energy resources (increment 25% and 50%) in the microgrid on the OC relays protection performance.

B. LITERATURE REVIEW

In the literature, several Overcurrent (OC) protection schemes for microgrid protection have been used. Firstly, conventional OC protection schemes have commonly focused on using the well-known and practised OC curves characteristics, namely: definite-time, inverse-time, instantaneous, and mixed curves, based on calculating the load and fault current level and direction [8]–[10]. However, conventional OC relays approaches have a limited performance within microgrid systems, where it does not consider the impact of DG and renewable energy resources on the network power flow, fault characteristics and the protection system [7], [10]. Recently, there is limited literature on developing and designing OC relays protection schemes for a power network grid incorporating DG or renewable energy sources. In [11], [12], a new framework for OC relays coordination was developed to design a protection scheme for the microgrid system. The authors in [11] suggested a new model constraint (setting groups) by considering the upper limit of the Plug Setting Multiplier (PSM) as a variable. In [12], a central protection controller was developed as an online adaptive OC relays scheme to respond to the different operation modes of the microgrid. However, the proposed schemes in [11], [12] were not suitable for the minimum fault current with high impedance. Therefore, authors in [13]–[15] described the OC relays coordination problem as an optimization problem. In [13], the authors used a swarm optimization algorithm to solve the OC relays coordination problem. The Particle Swarm Optimization (PSO) and integer linear programming are presented by [14] to find the optimal setting of OC relays. Similarly, the K-means algorithm [15] and Self-Organizing Map (SOM) clustering algorithm are employed to adapt the setting of OC relays for the microgrid network. However, the previous literature [13]–[15] focused on developing an optimal OC protection scheme, which is solved by a common optimization algorithm based on using standard schemes such as inverse time characteristics to achieve faster OC protections. This shows that developing and employing a new and powerful optimization algorithm such as metaheuristic optimization algorithms or machine learning algorithms can be beneficial for improving the OC relays performance and solving the relays coordination problems in a microgrid. For example, the authors in [13], [16] developed an adaptive optimal protection system based on using a hybrid model; artificial neural network and Support vector machine model in [16] and swarm optimization algorithm with a fuzzy algorithm in [13]. However, it will require real-time network information through communication links to determine the OC relays setting. In addition, the adaptive and hybrid models require establishing a communication system which costly and complex option. This paper aims to present an optimal OC relays coordination approach based on a new metaheuristic optimization algorithm and it doesn't require a communication link to reduce the computational cost. Furthermore, four new and powerful metaheuristic optimization algorithms, namely: Modified Particle Swarm Optimization (MPSO), Teaching Learning (TL), Grey Wolf Optimizer (GWO) and Moth-Flame Optimization Algorithm (MFO) were used for solving the proposed coordination model and compared them to the common algorithm from the literature, PSO. The increasing of DGs in the distribution networks makes the OC relays coordination an increasingly complex problem.

Recently, various researchers have presented the nonstandard curve characteristics as a potential solution for the protection coordination problem in microgrids [17], [18] and using the metaheuristic optimization algorithms [19]. In [12] and [20], the OC coordination problem is described as an objective function with several constraints and they used the GA method to achieve the minimum operation time for the relays by finding the optimal settings for the OC relays. However, the proposed OC coordination approaches in [12], [20] did not treat or deal with the stochasticity of the microgrid operation modes. Therefore, authors in [17], [18], [21] modified the cost function of the OC relays coordination problem to treat the complexity of the microgrid operation modes by using for example new time-current-voltage characteristics [21] or a non-standard time characteristics [17], [18]. The nonstandard curve characteristics aim to improve the performance of the OC protection scheme for different operation modes of the microgrid. For example, the authors in [17] developed an OC protection coordination approach by modifying the constants of the time characteristic curve. Then an optimization algorithm solves the optimization problem for the nonstandard curve to reduce the total operation time [17]. The authors [7] employed a nonstandard tripping characteristic, which depends on the fault level and location and aims to reduce the tripping time. In the literature, various solution techniques have been developed to find the optimal coordination of OC relays in microgrid systems.

In this work, an optimal OC relays coordination scheme using a nonstandard curve and four new and powerful metaheuristic optimization algorithms (MPSO, TL, GWO and MFO) is developed to increase the protection performance in terms of sensitivity selectivity and speed by minimizing the total tripping time compared to conventional and optimal OC relays schemes from the literature. In addition, several tests will be performed on a benchmark International Electrotechnical Commission (IEC) microgrid by considering different levels of renewable energy resources contributions in the microgrid.

C. CONTRIBUTIONS

The literature raised many concerns and presented challenges in terms of using conventional OC relays characteristics for a microgrid. These concerns and challenges are mainly in terms of stability, security, protection sensitivity, power flow and ability to accommodate emerging renewable energy resources to the network. This showed the need to develop flexible and optimal OC relays protection schemes to securely protect the microgrid system or modern distribution networks with renewable energy resources. In this work, an optimal OC relays protection scheme based on using four modern metaheuristic optimization algorithms (MPSO, TL, GWO and MFO) to provide a fast response OC protection and improve the OC relays coordination performance for a power network equipped with renewable energy (Photovoltaics (PV) and wind) resources. To evaluate the effectiveness of using the proposed optimization algorithms in solving the OC coordination problem, the results were compared with conventional and a new protection scheme and common optimization algorithm from the literature [7], [14] in different operational modes. In addition, aiming to fill the gap in the literature, this article designs the proposed optimal scheme as a non-communication protection scheme based on using new non-standard OC curve characteristics. A summary of the main contributions of this work are as follows:

I. A new optimal OC relays protection scheme based on using nonstandard tripping curve characteristics to improve the sensitivity, selectivity and OC relays coordination performance compared to the literature [11]–[17] and standard inverse tripping curve [8]–[10] for a power network connected to stochastic DG sources. The proposed scheme aims to minimize the total tripping time for OC relays compared to conventional [8]–[10] and optimal schemes [11]–[17] used in the literature. In this work, a significant reduction in the overall tripping time is achieved and no record of miscoordination between the OC relays. In addition, the proposed optimal OC relays protection scheme is a non-communication protection system and it aims to reduce the cost, and computational cost by minimizing the need for communications infrastructure or access to large quantities of power network data. The proposed optimal OC relays protection scheme as a non-communication system can provide sufficient stability and robustness to the OC relays protections.

II. Modern metaheuristic optimization algorithms (MPSO, TL, GWO and MFO) are developed and employed in this work to solve the OC relay coordination problem and improve the protection scheme performance. The metaheuristic optimization algorithms showed a powerful ability to achieve a global solution for different engineering problems and outperformed common algorithms such as PSO and Genetic Algorithm (GA) [7]. Therefore, this work introduces and employs these modern algorithms in solving complex OC coordination problems for a power network equipped with stochastic DG sources. To the authors knowledge, there are no studies on using and comparing these modern algorithms in solving modern OC relays coordination problems in a microgrid. In addition, a comparison analysis for using the modern metaheuristic optimization algorithms in OC protection scheme on different operational modes for the power network. In this work, the new metaheuristic optimization algorithms (MPSO, TL, GWO and MFO) are compared to the common and standard algorithm (PSO) from the literature.

III. Finally, the impact of integrating the different levels of renewable energy resources (increment 25% and 50%) in the microgrid on the OC relays protection performance is tested and evaluated. Comparison analysis for the proposed optimal OC relays protection scheme under different fault scenarios in different levels of renewable energy resources on an IEC microgrid is introduced in this work to give the operators an initial indicator about the possible impact of increasing the renewable energy resources on the protection system. In addition, unlike the previous studies [11]–[15], the sensitivity of the proposed optimal OC relays protection scheme has been tested and greatly improved for higher impedance fault. This test aims to evaluate the capability of the proposed scheme to accommodate different operational modes of microgrid such as the islanded operation mode.

D. OUTLINE OF PAPER

This article is organized as follows: the problem description is presented in Section II. Section III introduces and illustrates the novel optimal OC relays protection scheme based on using the new nonstandard curve characteristic and different modern metaheuristic optimization algorithms. The network model details and simulation results are presented and discussed in Section IV. Finally, the conclusions of this work are presented in Section V.

II. PROTECTION-COORDINATION PROBLEM DESCRIPTION AND FORMULATION

The sensitive protection scheme for a power network connected to DGs such as renewable energy sources is an important tool to maintain the safe network operation and reliability of the system [4],[7]. To illustrate the OC relay coordination problem, an example of a single line diagram for a power distribution network is presented in Fig.1 [7]. The distribution network includes two power sources (main grid and DG), and three lines protected by three OC relays. In Fig.1, the OC relays (R_1, R_2 and R_3) are coordinated from the demand to the power sources sides. Therefore, the primary relay at fault F_1 is R_1 and R_2 will operate with a delay as a backup relay.

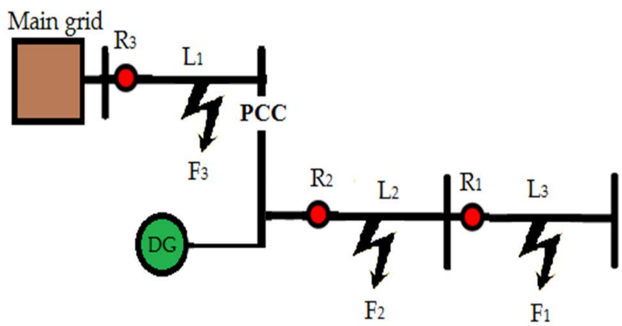


FIGURE 1. Single line diagram of a power distribution network with DG.

In the traditional network (without DGs), the OC relays coordinate with Coordination Time Interval (CTI) between 0.2 to 0.5 Sec, as shown in Fig.2. This normally causes stress on the power network due to the long operating time of OC relays and the high probability of entering the definite time region when the maximum fault scenario occurred (fault at the region close to the power source) [4], [7]–[9].

The fault characteristics for a power network connected to DG will be different in terms of level and direction, which increase the complexity and challenges of protecting the network using the conventional OC scheme. In general, the DGs such as renewable energy sources have a stochastic behaviour, which leads to creating a wide range of the minimum and maximum fault current levels. Therefore, the conventional OC scheme will face many problems to satisfy the selectivity, sensitivity, and speed protection system requirements [4]–[7]. Fig.3 introduces the impact of integrating DGs into the power network and the fault current. For example, the maximum fault current at R_2 increased in the case of connecting DGs to the network compared to the fault current at the network without DGs. On the other

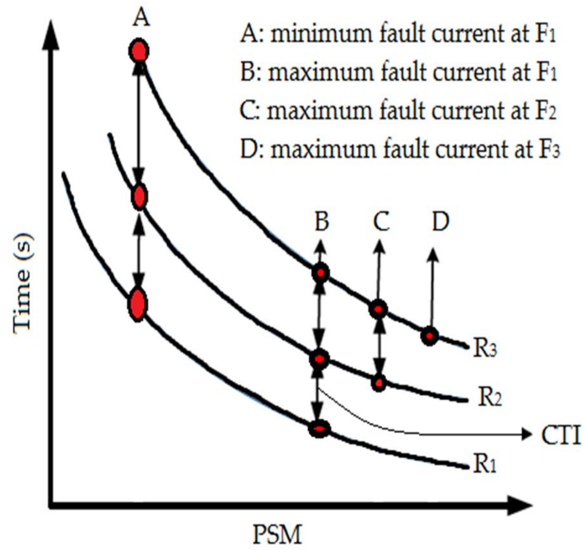


FIGURE 2. The OC relays coordination between main and backup relays at a power network without DG [7], [9].

hand, the maximum fault current for the network with DGs at R_3 decreased compared to the maximum fault current at the network without DGs. Therefore, in case of fault occurs at F_2 for a power network connected with DGs, the fault current level will increase at R_2(primary relay) and it will decrease at R_3 (backup relay), which causes a failure in the OC relays coordination or disconnecting time delay [7], [8].

As shown in Fig.3, the fault level has been changed from a network without DGs to a network connected to DGs. This is mainly related to the new power network topology, power flow calculations, different operation modes and changes in fault resistance and location. The varied level of fault currents at the network with DGs will cause a miscoordination for OC relays. For instance, the backup relay (R_3) may not operate if a failure condition occurred at R_2 for the islanding mode (minimum current fault), where the fault current value will decrease compared in the power network with DG compared to the network without DGs.

In power networks equipped with DGs, the fault current will be too small within the islanding scenario, which increases the challenges of detecting the fault current by using the conventional scheme [7], [10]. Therefore, it is significant to develop and design a new OC curve characteristic to handle these protection challenges and react to different microgrid operation modes such as grid-connected and islanded modes. In this article, to overcome these modern challenges in the power network, various intelligent optimal protection schemes using nonstandard curves are developed. This proposed optimal OC coordination scheme aims to calculate the Plug Setting Multiplier (PSM), which minimizes the total operational times of OC relays under the Coordination Time Interval (CTI) constraints and with no record of miscoordination. The proposed coordination scheme is designed to be compatible with the different operational conditions of

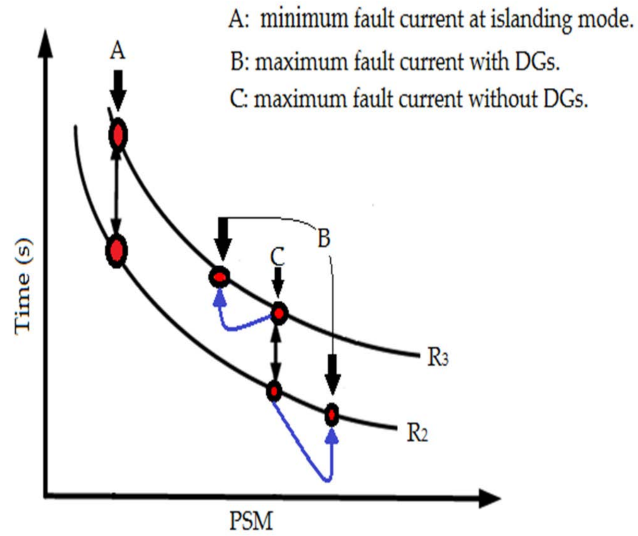


FIGURE 3. The fault characteristics and OC relays miscoordination at a power network with DGs [7], [8].

microgrid topologies. Therefore, the CTI constraints and the operating time for OC relays based on conventional characteristics are described in the following subsections.

A. CONVENTIONAL RELAY OPERATIONAL CHARACTERISTICS

In the conventional OC relays scheme, the coordination time between the relays is determined based on assumption that the power network parameters and fault current characteristics will not change. The CTI as minimum coordination time between the main and backup relays (R_2 and R_3, respectively) for a fault (F_2) as an example will be mathematically described in Equation 1 [3], [7]–[9].

$$t_{R3} - t_{R2} \geq CTI \tag{1}$$

The changes in the characteristics of fault current due to connecting the DGs to the power network will lead to reducing the time interval ($t_{R3} - t_{R2}$) to less than the acceptable CTI and then causes a miss-coordination status between OC relays, as shown in Fig.3 and discussed in Section 2 [7], [10]–[13]. The operating time, t, for OC relays is calculated based on conventional methods and relay standard characteristics, as described in Equations 2 and 3.

$$t = \left[\frac{\text{A}}{\left(\frac{I_{sh}}{I_p}\right)^{\text{B}} - 1} \right] \times \text{TMS} \tag{2}$$

$$t = \left[\frac{\text{A}}{\left(\frac{I_{sh}}{I_p}\right)^{\text{B}} - 1} + C \right] \times \text{TMS} \tag{3}$$

where I_{sh} is the fault current (short-circuit), I_p is the relay pickup current and Time Multiplier Setting is the TMS. The A, B, and C are coefficients, in Equations 2 and 3, are defined based on the relay standard, as described and presented in [7], [22]–[24]. The standards of OC relays are classified into Institute of Electrical and Electronics Engineers (IEEE) [22], IEC [23] and the AREVA [24] standards. The three main standards are designed to work with three main curves as follows: Normal Inverse (NI), Very Inverse (VI) and Extremely Inverse (EI).

B. FORMULATION OF OC RELAYS COORDINATION PROBLEM

In this work, the OC relays coordination problem in a power network equipped with renewable energy resources (DGs), as described in Section 2.1, is formulated as an optimization problem. This formulation aims to help the operator find the optimal TMS that minimizes the total operation times of OC relays without any miss-coordination events. In this section, the mathematical formulation of the OC relays coordination optimization problem is presented. The proposed optimization problem will be solved by different Modern metaheuristic optimization algorithms to improve the protection system performance in microgrids compared to conventional protection schemes.

1) COORDINATION PROBLEM: OBJECTIVE FUNCTION AND CONSTRAINTS

In the OC relays coordination problem, the TMS value, in Equations (2) and (3), is the key element to manage the operating time of OC relays, t. Therefore, it is required to develop an objective function, OF_{relays}, minimizing the total operating time, t, of all OC relays (primary and backup) within the TMS constraints. The mathematical formulation of the OC relays coordination problem is described by Equation (4). The OC coordination problem is described as a single objective function where the aim is to minimize the OF_{relays} for several relays equal to X, at different total fault locations equal to Y, [5], [7]. The formulation of the OC coordination problem in Equation (4) helped to simplify the objective function compared to using multi-objective optimization methods. The multi-objective will require involving different objective functions, different orders of magnitude, transforming into a single objective by normalizing the objective functions. This process in multi-objective optimization methods will require more computational costs and effort to achieve an optimal solution compared to the proposed solution in this paper [7].

$$OF_{relays} = \sum_{x=1}^{X} \sum_{y=1}^{Y} t_{x,y} \tag{4}$$

The OF_{relays} needs to be solved under the number of model constraints. The constraints of the OC coordination problem are described as follows:

a: COORDINATION CRITERIA

One of the main requirements in the protection system is selectivity, which depends on the coordination constraint.

The coordination criteria aim to add a delay operation time between the primary and backup relays. This process aims to give the primary protection relay sufficient time to clear the fault before allowing the backup relay to operate in case of failure in the primary protection relay. The selectivity and coordination criteria work on minimizing the network outages based on isolating only the fault location. The selectivity and coordination criteria are described by the CTI as a set of inequality constraints. The CTI is the minimum coordination time between the main and backup relays (t_{back} and t_{primary}, respectively), as presented in Equation 5.

$$t_{\text{back}} - t_{\text{primary}} \geq CTI \tag{5}$$

In general, the CTI value, in seconds, takes into account several parameters in the protection system such as the computational cost for the relay, type of relay and circuit breaker speed to react. Normally, the CTI is determined between 0.2 and 0.5 s based on the IEEE-242 to achieve the protection system requirements of selectivity [4], [8]. Therefore, the CTI is set to 0.3 s, in this work, within the standard margin [4], [7], [19].

b: LIMITS ON TSM AND THE OPERATING TIME OF RELAY

In general, the OC relays should operate quickly within the minimum possible operation time to achieve faster OC protections and avoid any delay, which may cause damage and instability in the network. To maintain the operational time limitations, constraints need to be presented for the minimum and maximum for the operational times of OC relays and TMS. Therefore, the minimum and maximum operational time for OC relays is set as bounds in Equation (6) and for TMS in Equation (7).

$$OT_{min} \leq OT_n \leq OT_{max} \tag{6}$$

$$TMS_{min} \leq TMS_n \leq TMS_{max} \tag{7}$$

where OT_{min} is the minimum operational time and OT_{max} is the maximum operational time at primary relay n. The minimum and maximum TMS values at primary relay n are TMS_{min} and TMS_{max}, respectively [7]–[10]. In this work, the TMS variable has been treated as a continuous variable. The OC relays need to take action within the operation time limits for different fault conditions. Therefore, the Plug Setting Multiplier (PSM) is selected within the maximum and minimum limitations based on the fault current level seen by the relay (maximum and minimum) and the load level as light load or overload. In general, the PSM limits start from 1.1 to 20 times of PSM for OC relays in industrial and microgrid applications [4], [7], [19]. In this paper, the PSM limits vary between 1.1 and 100, where the PMS has been extended to 100 instead of 20 times of PSM to cover the different increases in the DGs and fault current levels in the microgrid. In general, the PSM describes as the ratio between the fault current I_{sh} and the relay pickup current, I_p, $PSM = I_{sh}/I_p$.

In general, the fault current characteristics (level and direction) passing through the R_2 and R_3 (main and backup relays, respectively) has changed as described in Section 2 and shown in Fig.3. Therefore, the conventional OC relays scheme, as described in Equations 2 and 3, cannot be efficient to coordinate the OC relays and it is important to employ and develop a new protection scheme. Nowadays, numerical protection relays such as OC microprocessor relays have the ability to change the time curve characteristics and create new tripping curve characteristics (nonstandard). These nonstandard time characteristics aim to minimize the relay tripping time and improve the relay performance for minimum faults conditions. In addition, the OC microprocessor relays allow user-defined and nonstandard curves to handle the protection challenges within microgrid systems [25]–[27]. The following section will present the proposed protection scheme based on nonstandard time characteristics.

III. PROPOSED PROTECTION APPROACH

In the objective function and constraints of the OC protection problem, the main objective of the OC relays coordination process is to determine the optimal TMS value, which minimizes the total operational time. In general, the NI characteristic is widely used in the literature [22] as a common and stander curve. However, the NI has a limited performance to low and high values of PSM, as described in Section 2. In addition, the fault characteristics (level, location and direction) are different for a power network connected to DGs compared to the traditional network without DGs. This limitation will decrease the sensitivity of OC protection systems in the modern network and microgrid system, where is a wide range of the minimum and maximum fault current levels [7]–[9], [19]. To improve the OC protection system performance and overcome the NI characteristic limitation in the microgrid system, this work proposed an advanced optimal OC relays coordination scheme based on modern metaheuristic optimization algorithms and using a nonstandard tripping characteristic. Furthermore, a comparison analysis for different optimization coordination models based on standard and nonstandard tripping characteristics is presented [7], [17]. The basic framework for the proposed OC relays coordination approach is shown in Fig.4 [7]. Firstly, the IEC microgrid including different power sources (utility grid and renewable energy sources) is implemented. To determine the optimal relay setting, the fault currents and load levels will be calculated in different locations based on IEC60909. Then, the OF_{relays}, Equation 4, will be solved by using four modern metaheuristic optimization algorithms (MPSO, TL, GWO and MFO) to find the optimal TMS for OC relays based on standard and nonstandard curves. In the literature, the MPSO [28], [29], TL [19], [30], GWO [1], [31] and MFO [1], [32] algorithms showed a powerful performance in solving complex engineering problems and stochastic behaviour by considering a different number of possible solutions at each iteration [1], [7], [19]. Therefore, these modern metaheuristic optimization algorithms can be beneficial in improving the

OC relays performance and solving the relays coordination problems in a microgrid. In this study, the MPSO, TL, GWO and MFO algorithms are used to calculate the OC relays setting (TMS) in the MATLAB environment as the computational software. Then, the obtained and calculated optimal OC relays setting (TMS) by the MATLAB software will be verified using an industrial power systems analysis software, called ETAP, under different fault conditions. The ETAP and MATLAB programmers are interconnected and equipped based on a co-simulation framework. This combination aims to present the network and the proposed protection model close to the real network by combing the capabilities of these programmers in solving the optimization problem in microgrid by MATLAB and then verifying the protection performance using the ETAP. The modern metaheuristic optimization algorithms are developed to solve the coordination problem by using nonstandard tripping characteristics and compared to the conventional standard protection scheme. In the following section, the nonstandard tripping characteristic is described and formulated as a solution to handle the microgrid protection challenges and overcome the limitation of the NI curve. Then, the MPSO, TL, GWO and MFO algorithms are presented and described to solve the OC coordination optimization problem.

A. A NONSTANDARD TRIPPING CHARACTERISTIC

In Fig.3, the conventional OC scheme (standard tripping characteristic) faced many problems and challenges to satisfy the selectivity and sensitivity requirements to protect a power network connected to DGs. Therefore, the nonstandard tripping characteristic is used and presented in this section. The proposed nonstandard tripping characteristic is followed the logarithmic function and is described by Equation (8) [7], [24]. The nonstandard logarithmic curve has been used to describe different applications, for example, the thermal limitations in transformers and cables and can be beneficial for OC coordination problems.

$$t = \left(5.8 - 1.35 * \log_e\left(\frac{I_{sh}}{I_p}\right)\right) * TMS \quad (8)$$

where I_{sh} is the fault current (short-circuit), I_p is the relay pickup current and Time Multiplier Setting is the TMS. To improve the selectivity performance of the OC relays coordination scheme, the grading time should be constant and independent of the fault characteristic (location and level). Therefore, the proposed nonstandard tripping characteristic based on logarithmic with constant coefficients will be effective and suitable for all relays [17], [33], [34]. As described in Section 2 and Fig.3, the NI curve faced many challenges to detect the minimum faults, especially when the DGs were connected to the grid. In Fig.5, the proposed nonstandard curve covers the minimum fault area sufficiently compared to the NI curve. This will help the proposed nonstandard curve to ensure the selectivity without any miss-coordination events or missing the time of tripping [7]. The TMS value in Equation (8) will be determined to provide the minimum total

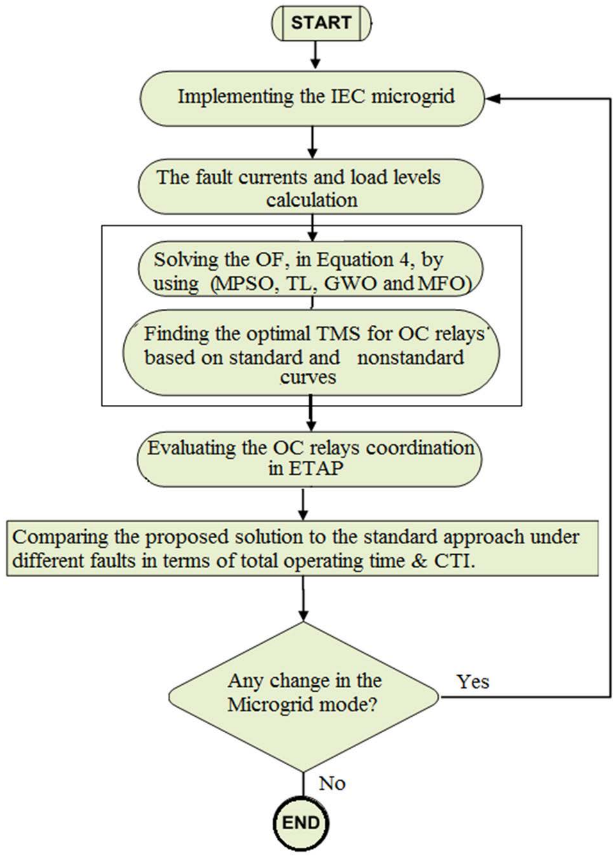


FIGURE 4. The proposed workflow for the advance optimal OC relays coordination scheme is implemented in this paper.

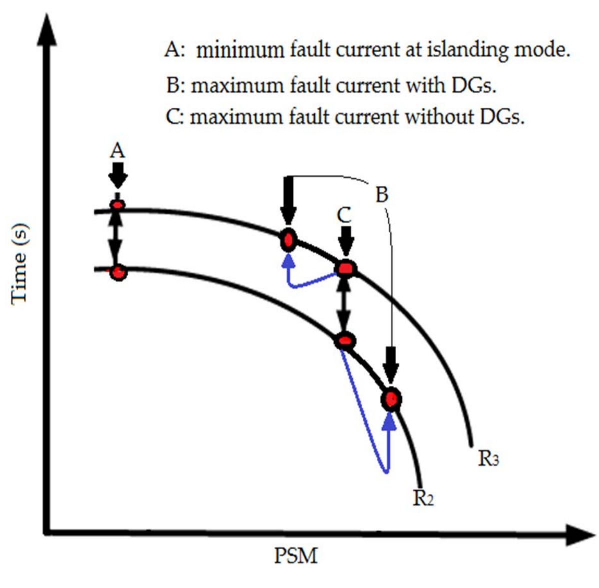


FIGURE 5. A nonstandard tripping characteristic [7], [22].

operation tripping time, in Equation 4, by using the MPSO, TL, GWO and MFO algorithms to solve the OF_{relays}. Thus, the nonstandard tripping characteristic will create an optimal grading time (optimal coordination) within the tripping time limits.

The OC relays coordination needs to be determined based on different fault locations. For example, if the fault is located near the power source, it will be within the maximum fault currents and if the fault is located at the end of the protected zone, the current will be within the minimum fault current. In this work, the maximum and minimum fault current scenarios are used for the CTI and the relay setting. The OC coordination scheme needs to guarantee the minimum operation time for the maximum fault current. As shown in Fig.6, the nonstandard curve provides at point B the lower operating time compared to the NI curve as a standard curve [7]. For point A, the tripping time of the OC relay will take longer for the minimum fault current. However, the nonstandard curve still provides a lower operating time compared to the NI curve at point A. In a microgrid system, the minimum fault current conditions will have occurred more than in the network without DGs. Therefore, the nonstandard curve can reduce the tripping time of OC relays and guarantee that there is no miss-coordination problem.

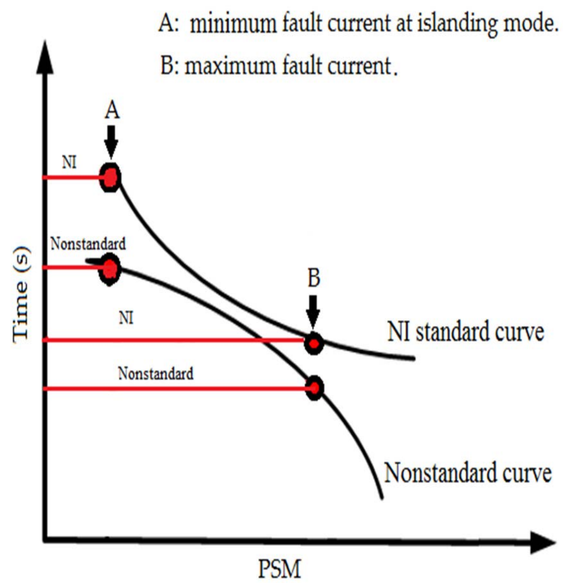


FIGURE 6. The nonstandard and NI standard curves [7].

B. PROPOSED METAHEURISTIC ALGORITHMS

In Section 2, the OC relays coordination problem is formulated and described as an optimization problem. The current literature has begun to investigate the benefits of solving different engineering problems as optimization problems by using new optimization algorithms and treating the challenges of adding renewable energy sources to the power network. In this paper, the modern optimization algorithms MPSO [29], TL [19], [30], GWO [31] and MFO [32] are adapted and employed to solve OC relays coordination problems and handle the stochastic nature of fault currents and load levels in the power network due to connecting the DGs. The newly proposed optimization algorithms are designed and developed to solve complex optimization problems most simply within a low computational cost. For example, the GWO and MFO require few numbers of adjustable parameters compared to other well-studied and common algorithms such as the Genetic Algorithm (GA) [7], [19]. Therefore, the proposed new algorithms (MPSO, TL, GWO and MFO) can be highly efficient and powerful algorithms for solving complex protection coordination problems for a power network integrated with DGs. Adequate new metaheuristic optimization algorithms for power networks, energy and engineering applications have a worldwide interest in energy saving, power system stability and power protection reliability. To the best of the author's knowledge, there is no study on OC relays coordination problems for a power network equipped with renewable energy resources that have used and compared the MPSO, TL, GWO and MFO algorithms to improve the performance of the protection system. Furthermore, this article introduces a comprehensive analysis of new metaheuristic optimization algorithms (GWO and MFO) and the powerful, common and recent algorithms from the literature (MPSO and TL) [28]–[32]. In this work, the proposed metaheuristic optimization algorithms parameters have been selected based on the optimal value within a specific range and the test details and models parameters will be discussed within Section 4.1.

1) MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

This subsection presents the MPSO algorithm, as described in Table 1, as a powerful optimization solver for complex problems such as OC relays coordination problems. The Particle Swarm Optimization (PSO) is one of the common and standard optimization algorithms that was introduced to solve different engineering problems by Kennedy and Eberhart [7], [14]. The simplicity of the PSO algorithm and fast convergence helped to use it in different electrical and energy applications such as power protection and power flow [28]. In general, the PSO algorithm is inspired by the different nature behaviours (human social and swarming animals) [19], [28]. In the PSO algorithm, the initial feasible solution as OC relays operating time profiles are generated based on the power network information, the load flow and short circuit calculations. The generated solution population is called swarm and each individual of the possible solution result will be called particle. Then the population will be evaluated by solving the OC relays coordination optimization problem, Equation (4) concerning the model constraints, Equations (5) to (8). The particles will memorize the current and best solution position in the population based on the population evaluation process. This information (the current and best solution position) will be used to update the swarm information and adjust the particle trajectory. In each iteration, the current and best solution positions are closed to the optimal by moving the particle in the swarms towards the optimal solution, as a ''global solution'' for the OC relays coordination problem and the PSM will be selected. However,

TABLE 1. The MPSO model procedures.

Steps	Description
Step 1: Initialize the population	-Implementing IEC microgrid. -Calculating the load flow and short circuits. -Initializing the feasible solution for the OC coordination problem (operating time profiles)
Step 2: Population evaluation	Calculating and evaluating each solution by solving the OC relays coordination optimization problem, Equation (4), under constraints, Equations (5) to (8).
Step 3: Updating swarm information	The swarm information (the current, best solution position and all particles' mistakes) will be used to adjust the particle trajectory
Step 4: The optimal solution for the OC relays coordination problem and selecting the PSM.	The MPSO is an iteration process, therefore, the above steps from 2 will be repeated until achieving the maximum number of iterations.

in recent research, several modifications to the standard PSO are introduced to improve the convergence speed and robustness terms. This work presented the Modified PSO (MPSO) as a faster solution for the OC relays coordination problem. The main idea of the proposed modification of PSO is not only to learn from the current and best particles but also all particles [28], [29]. This modification aims to improve the performance and robustness of the optimization solver. The main procedures of the MPSO for solving the OC relay coordination problem.

2) TEACHING LEARNING (TL)

The TL methodology is inspired by the dynamics and nature of the teaching process in a classroom [19], [28]. In energy and power system applications, the TL has been employed to handle complex power flow and protection coordination optimization problems [28]. However, the power protection studies typically only use TL to solve the coordination optimization problem, which utilizes a stander time inverse curve (NI). The TL is applied as an iterative algorithm to improve performance and solve complex optimization problems [30]. In each iteration, the TL considers different possible solutions to achieve the optimal one. In Fig.7, the flow chart of the TL algorithm for the OC relays coordination problem is presented. Firstly, the TL randomly generates a population as the initial feasible solution (OC relays operating time profiles). This population is labelled as learners and each learner (possible solutions) will be evaluated based on a fitness function. Here, the fitness function is the objective function of OC relays coordination problem, Equation (4) concerning the model constraints, Equations (5) to (8). Then, the best solution based on the evaluation through the fitness function will be marked as a teacher. The TL algorithm is divided into two main stages; namely: Teacher and Student. In the first stage, the Teacher stage, the potential solutions, as the OC relays operating time profiles, for the OC coordination problem, are marked as students. The student will modify and improve their knowledge, moving towards an optimal solution, based on the best solution result (teacher) from the evolution process. In the TL algorithm, each possible solution (student) must go through the two stages at every iteration. The TL algorithm requires only two adjustable parameters (umber of iterations and size of the population) compared to the other techniques from the literature, which helped to consume less time and to be easy to implement. In Fig.7, the TL algorithm is described and presented, where OT_n are the candidate solution n (relay operational time and known in TL as student or learner) and the random process is presented by r as a random number. The TL algorithm is a greedy search process in both stages, where the new solution will be acceptable if only outperform the previous one.

3) GREY WOLF OPTIMIZER (GWO)

A new bio-inspired metaheuristic optimization algorithm called Grey Wolf Optimizer (GWO) has been designed and introduced by Mirjalili *et al.* [1], [31]. The GWO is presented by [31] as a new metaheuristic algorithm for solving stochastic optimization problems and the results of [31] showed that the GWO outperformed common metaheuristic algorithms, such as differential evolution and evolutionary programming algorithms, in 29 well-known test functions. Therefore, the GWO can be beneficial in solving the OC relays problem in a power network equipped with DGs. To the best of the author's knowledge, there is no study on OC relays coordination problems have used and compared the GWO algorithm to improve the performance of the protection system. The main concept of GWO is inspired by the intelligent activities of grey wolfs (Canis lupus) [1], [31]. The GWO follows the leadership wolf movements and their hunting mechanism. The GWO mimics based on three stages, namely: tracking, encircling, and attacking prey, as shown in Fig.8. In the first stage, the initial feasible solution (OC relays operating time profiles) which presented wolfs are generated based on the power network data. Then wolfs (solutions) will be evaluated by solving the OC relays coordination optimization problem, Equation (4) concerning the model constraints, Equations (5) to (8). The wolfs will be arranged in order from the fittest solution to the worst wolf position or solution. In the following stage, the encircling prey stage, the grey wolfs (current position) will be updated based on the position of the prey (the best solution) and random locations. However, the fittest three solutions will be saved (they may close the optimal solution, prey) and only the rest of the solution will be updated as part of the hunting process. The new solutions will be evaluated and rearranged the fittest solutions based on the new results. Finally, the hunting process (updating the solution, wolfs position) will finish when the prey (best solutions) stops moving or changing, which mean that the model achieved the optimal solution.

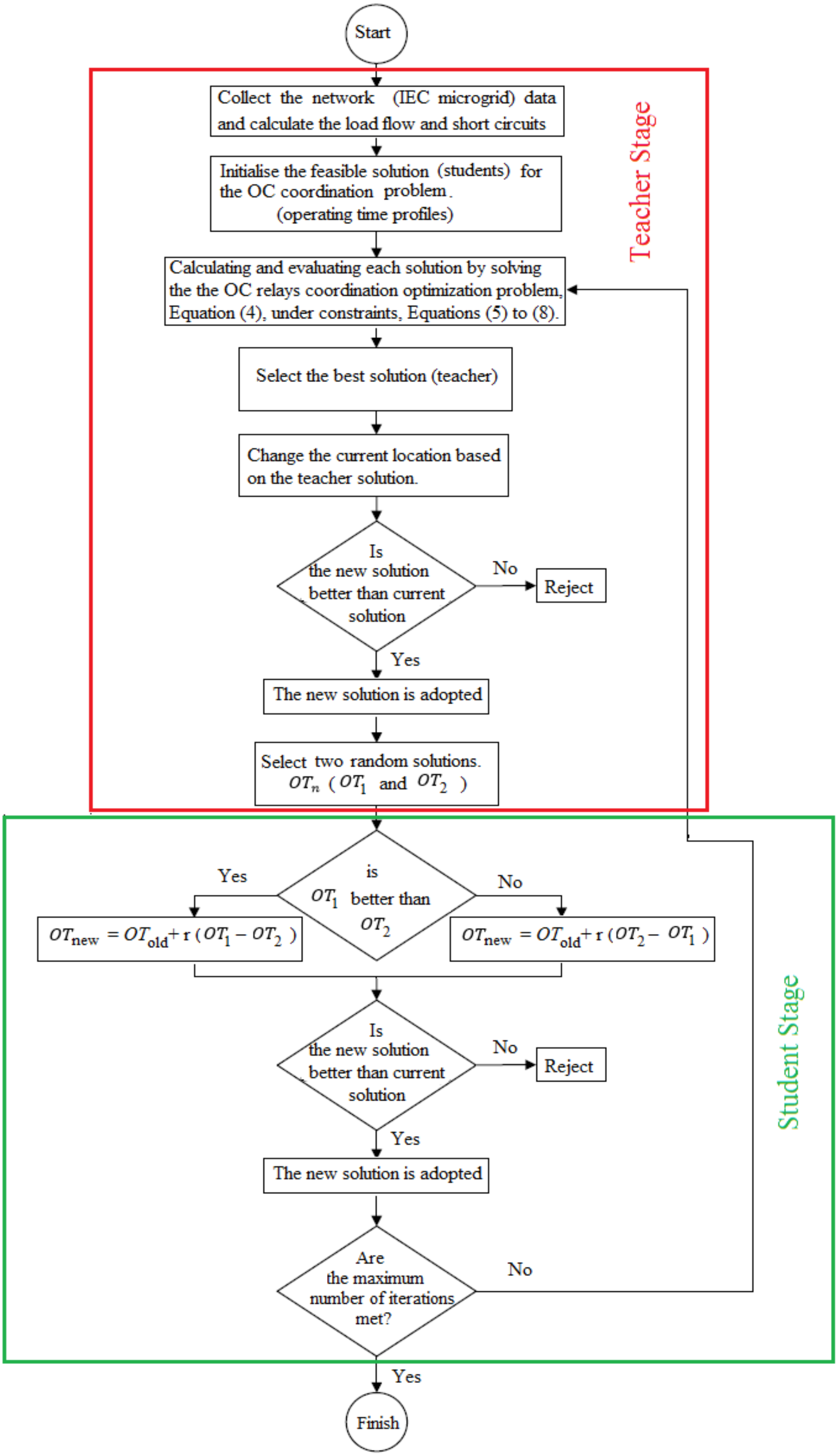


FIGURE 7. **A flow chart of teaching learning (TL) for OC relays coordination problems.**

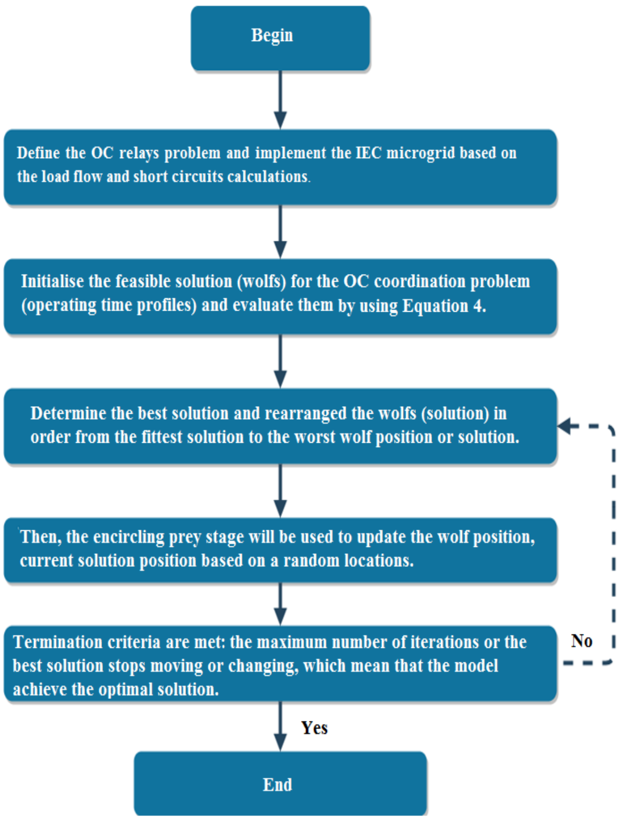


FIGURE 8. A flow chart of grey wolf optimizer (GWO) for OC relays coordination problem.

4) MOTH-FLAME OPTIMIZATION ALGORITHM (MFO)

The MFO is inspired by the navigation method of moths in nature. The moving of moths in the night towards lights based on maintaining a fixed angle is presented as an effective mechanism to achieve the objective. The MFO is introduced by [32] as a new metaheuristic algorithm for solving complex optimization problems and the results of [32] showed that the MFO outperformed common algorithms, such as PSO and GA, in 29 benchmark tests and 7 real engineering problems. Therefore, the MFO can be presented as a promising and powerful solution to solving the OC relays problem in a power network equipped with DGs. There is no study on using MFO on solving the OC relays coordination problems and improve the performance of the protection system. The main concept of MFO is followed by the moths moving process towards the flame [1], [32], as presented in Table 2. In the first step, the candidate solutions (OC relays operating time profiles) presented the moths. These solutions are generated based on the power network data. The OC relays coordination problem's variables (OT_n and TMS) are the position of moths in the space. Then, the moths (candidate solutions) will be evaluated based on a fitness function (objective function). In this paper, the fitness value is calculated by solving the OC relays coordination optimization problem, Equation (4) concerning the model constraints, Equations (5) to (8).

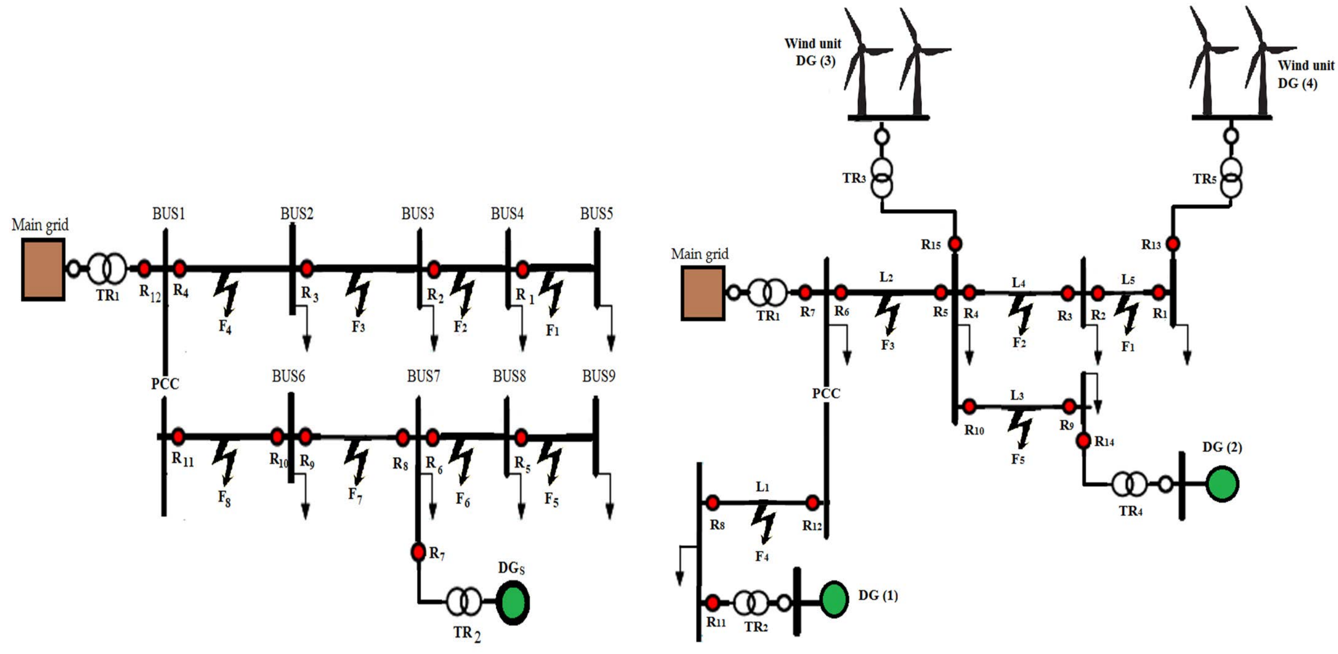
In the following stage, the moths as search agents will update their position based on the position of the flame (the best solution from the previous step) and random moth locations. The new moths positions (solutions) will be evaluated by using the fitness function. Finally, the moths moving process will stop when the moth and flame (best solutions) are in the same position, which means that the model achieved the optimal solution, or achieved the maximum number of iterations.

TABLE 2. The procedure of the moth-flame optimization algorithm (MFO).

Steps	Description
Step 1: Initialize the population	-Implementing IEC microgrid based on the load flow and short circuits calculations. -Initializing the feasible solution (moths) for the OC coordination problem (operating time profiles)
Step 2: Population evaluation	Calculating and evaluating each solution (moths) by solving the OC relays coordination optimization problem, Equation (4), under constraints, Equations (5) to (8).
Step 3: Selecting the best solution	The best solution position (flam) is determined and all moths positions will be updated based on the flam position
Step 4: The optimal solution for the OC relays coordination problem and selecting the PSM.	The MFO is an iteration process, therefore, the above steps from 2 will be repeated until achieving the maximum number of iterations or the moths and flame (best solutions) are in the same position.

IV. SIMULATION RESULTS AND DISCUSSION

The proposed protection approach for OC relays coordination problem, as discussed in Section 3, and the formulation of the miss-coordination problem in Section 2, are tested and evaluated using a benchmark IEC microgrid with different operation scenarios and different types of faults. The proposed nonstandard tripping characteristic and NI curve were applied and compared to protect a network equipped with/without DGs. In this section, the results of the proposed nonstandard tripping characteristic approach and the new optimal algorithms (MPSO, TL, GWO and MFO) are presented and discussed. Firstly, the description of the IEC microgrid and the operating model for the network are presented. Then, the nonstandard tripping characteristic approach was tested under different operational models and fault scenarios for the IEC microgrid. The nonstandard approach is compared to the traditional inverse time scheme (NI), both approaches are used to solve the optimal OC coordination problem by using the common and standard algorithm (PSO) [7], [19], [33]. In addition, the comparison in terms of overall operational time for the relays and the computational cost for solving the optimal coordination problem over different network scenarios are presented. In this section, the new optimal algorithms (MPSO, TL, GWO and MFO) are employed to solve the OC relays coordination problem using the standard and nonstandard time curves. The results of MPSO, TL, GWO and MFO algorithms are compared to the common



a) IEEE 9 bus microgrid.

b) IEC microgrid

FIGURE 9. Single line diagram of the power network models a) IEEE 9 bus microgrid. b) IEC microgrid.

and standard algorithm (PSO) in different network scenarios. Finally, the proposed nonstandard tripping characteristic and the proposed new optimization methods have been evaluated and tested using Industrial software (ETAP) and the results are compared to the traditional standard approach.

A. DESCRIPTION OF THE NETWORK MODELS UNDER STUDY

In this paper, two benchmark power network models are used to test and evaluate the proposed OC coronation approaches. Firstly, the IEEE 9 bus microgrid system is used as a common radial system for protection studies [7]. This common power network, as shown in Fig.9(a), is included two feeders based on the Canadian Urban Benchmark power distribution model with a 4-bus feeder [7]. The IEEE 9 bus system is fed by the utility grid (500 MVA) through a transformer (20 MVA, 115 kV/12.47 kV). In addition, the IEEE 9 bus network is equipped with DG s (20 MVA). Twelves OC relays are employed in this network with two-directional OC relays (R8 and R10) to deal with the contribution of DGs to the fault. The size and specifications of the proposed power network (IEEE 9 bus) and DGs system are described in detail in [7]. Secondly, the IEC microgrid includes different types of DGs [7], [33] is used as a larger and more complex network model with different operations and integrating levels of DGs. The IEC microgrid, as shown in Fig.9(b), includes mainly four synchronous units of DGs (two synchronous generators and two wind turbines) and five transformers. The details of the IEC microgrid are given in Table 3 from [33], [34]. In the simplified IEC microgrid, as shown in Fig.9(b), 15 OC relays are employed to protect the network with five directional OC relays (R1, R3, R5, R8 and R9). The five directional OC relays aim to protect the network from the contribution of the DGs to the fault. The OC relays information (Current Transformer Ratio (CTR), Plug Setting (PS) and Pickup Current (IP)) for each OC relay are presented in Table 4 for the IEEE 9 bus and IEC microgrid system. This OC relays data will be used to simulate the IEC microgrid model. In this study, different faults have been simulated when all DGs are connected in for the IEEE 9 bus and IEC microgrid system. In each fault scenario, two OC relays are assigned as primary relays with one backup relay for each primary relay, as presented in Section 4.2. In addition, the value of PSM for each OC relay overall fault scenarios are calculated and discussed in Section 4.2. The PSM is calculated based on the maximum load currents in line with the primary OC relays where it needs to react very fast. The backup OC relays will operate concerning a CTI equal to 0.3 Sec. The OC relays have a different setting and PSM related to the type and location of faults. In addition, the fault calculation for different scenarios is generated according to the IEC-60909 [7], [34].

B. THE PERFORMANCE OF NONSTANDARD APPROACH IN THE STANDARD POWER NETWORK

The Nonstandard Tripping Characteristic (NTC) approach was tested under different operational models and fault scenarios for different IEEE 9 bus and IEC microgrid modes. The NTC approach is compared to the traditional inverse time scheme (NI), both approaches are used to solve the optimal OC coordination problem by using the common and standard

TABLE 3. The data and specifications of IEC microgrid.

Component	Size	Specifications
Main grid	Synchronous, MVA 1000	• Rated voltage 120 KV
DG1,DG2	Synchronous generator 9MVA	• Rated voltage 2.4 KV • Inertia Constant H=1.07s • Friction factor F=0.1pu • Rs=0.0036pu,Xd=1.56pu • Xd'=0.296pu,Xd''=0.177pu • Xq=1.06pu,Xq''=0.177pu • X1=0.052pu,Td'=3.7s • Td''=0.05s,Tqo''=0.05s
DG3	Three wind turbines Type4, 2MVA	• 6MW,Pf=0.9 • Rated voltage 575 V • Inertia Constant H=0.62s • Friction factor F=0.1pu • Rs=0.006pu,Xd=1.305pu • Xd'=0.296pu,Xd''=0.252pu • Xq=0.474pu,Xq''=0.243pu • X1=0.18pu,Td'=4.49s • Td''=0.0681s,Tqo''=0.0513s
DG4	DFIG based wind farm consists of six 1.5MVA	• 9MVA,Pf=0.9 • Rated voltage 575 V • Inertia Constant H=0.685s • Friction factor F=0.1pu • Rs=0.023pu,L1s=0.18pu • Rr'=0.016pu,L1r'=0.16pu • Lm=2.9pu
TR1	50MVA	• Rated voltage 120 KV/25KV • R1=0.00375pu,X1=0.1pu • Rm=500pu,Xm=500pu
TR2,TR4	12MVA	• Rated voltage 2.4 KV/25KV • R1=0.00375pu,X1=0.1pu • Rm=500pu,Xm=500pu
TR3,TR5	10MVA	• Rated voltage 575V/25KV • R1=0.00375pu,X1=0.1pu • Rm=500pu,Xm=500pu

algorithm (PSO) [7], [33]. In this section, the proposed non-standard OCR coordination scheme is evaluated by using two IEEE configurations: Scenario 1: the power network without DGs, Scenario 2: the power network with DGs, as shown in Fig.9(a). For scenarios 1 and 2, Table 5 shows the values for each OC relay and under all fault locations and conditions, Three-Phase Fault (LLL) and Line to Ground fault (LG).

In this work, the PS is calculated based on the maximum load currents under the condition that primary OC relays should operate very quickly. The backup OC relays are assumed to be running after with CTI equal 0.3 Sec.

To primarily evaluate the performance of the proposed OC coordination approach based on NTC compared to NI in terms of providing minimum operational time for all OC relays, Table 6 presents the overall operational time for all relays in scenarios 1 and 2. The result in Table 6 showed that the NTC approach outperformed the NI for both scenarios. The NTC recorded operational time for OC relays less than NI by 5.4% and 8.2% for scenarios 1 and 2, respectively. Furthermore, the results showed that in both approaches the operational time of relays has increased when the DGs has added to the power network (scenario 2) compared to a network without DGs (scenario 1).

C. COMPARATIVE PERFORMANCE USING THE NONSTANDARD AND NI TRIPPING CHARACTERISTIC FOR DIFFERENT IEC MODELS

In this work, to tackle the complexity of the OC relays coordination problem, a larger network system (IEC microgrid) with different operational modes has been employed to evaluate the proposed OC relays coordination approach based on NI and NTC schemes. Throughout this paper, we will test and evaluate the performance of OC relays coordination models based on the following network configurations:

- ✓ Model 1: the IEC microgrid, as shown in Fig.9 and described in Table 3. The system is fed from the main utility feeder and four DGs. This operation scenario aims to evaluate the performance of the OC relays as a standard power network with DGs.
- ✓ Model 2 and Model 3: the IEC microgrid has been modified by increasing the capacity of DGs by 25% and 50% for Model 2 and 3, respectively. These operation

TABLE 4. The OC relays data [current transformer ratio (CTR), plug setting (PS) and pickup current (IP)] for each OC relays for (a) IEEE 9 bus microgrid. (b) IEC microgrid.

(a)

Relay	CTR	PS	IP(A)
R1	100/1	1.128	112.8
R2	200/1	1.13	226
R3	300/1	1.132	339.6
R4	400/1	1.135	454
R5	100/1	1.128	112.8
R6	200/1	1.203	240.6
R7	300/1	1.204	361.2
R8	300/1	1.132	339.6
R9	300/1	1.132	339.6
R10	400/1	1.135	454
R11	400/1	1.135	454
R12	600/1	1.14	684

(b)

Relay	CTR	PS	IP(A)
R1	400/1	0.5	200
R2	400/1	0.5	200
R3	400/1	0.5	200
R4	400/1	0.5	200
R5	400/1	0.5	200
R6	400/1	0.5	200
R7	1200/1	1	1200
R8	400/1	0.5	200
R9	400/1	0.5	200
R10	400/1	0.5	200
R11	400/1	0.65	260
R12	400/1	0.5	200
R13	400/1	0.88	352
R14	400/1	0.65	260
R15	400/1	0.55	220

scenarios aim to evaluate the impact of adding DGs to the grid and increase the complexity of finding the optimal OC relays coordination.

In this study, different type of faults are applied to evaluate and test the proposed OC relays coordination schemes for all models as follow:

✓ Three-Phase Fault (LLL).

✓ Line to ground fault with ground resistance equal zero, R1 = 0 ohm, (LG-1).

✓ Line to ground fault with ground resistance equal five ohm, R1 = 5 ohm, (LG-2).

1) MODE 1 TEST RESULTS

In this subsection, different short-circuit faults are applied to evaluate and test the proposed OC relays schemes for Mode 1. Tables 7 and 8 present the short-circuit currents for the Three-Phase fault (LLL) and Line to Ground fault (LG-1) and the OC relays operational time for each relay (R1 to R15). Here, the plug setting for each relay is calculated based on the maximum load currents and the relays are assumed to operate within 0.3 Sec, and the backup relays will operate concerning CTI equal to 0.3 Sec. To demonstrate the significance of using the NTC curve compared to the traditional NI curve in terms of providing minimum operational tripping time under the constraints of CTI equal 0.3 Sec in different fault locations. Tables 5 and 6 present the LLL fault values and operation time OC relays in different fault locations for NI and NTC approaches. The NI approach recorded many delays in the

TABLE 5. The short-circuit currents values and PS under fault conditions for (a) Scenario 1, (b) Scenario 2.

(a)

Location of fault	LLL A	LLL PS	LG A	LG PS	Relay
F1	4380	38.8	4944	43.8	R1
	4378	19.3	4944	21.8	R2
F2	4882	21.6	5710	25.2	R2
	4882	14.3	5710	16.8	R3
F3	5496	16.1	6810	20.	R3
	5496	12.1	6810	15	R4
F4	6246	13.7	8575	18.8	R4
	6246	9.13	8575	12.5	R12
F5	4380	38.8	4944	38.8	R5
	4378	19.37	4944	21.8	R6
F6	4882	21.60	5710	25.2	R6
	4882	14.3	5710	16.8	R7
F7	5496	16.1	6810	20	R7
	5496	12.10	6810	15	R8
F8	6246	13.7	8575	18.8	R8
	6246	9.131	8575	12.53	R12

(b)

Location of fault	LLL A	LLL PS	LG A	LG PS	Relay
F1	4369	38.7	5003	44.3	**R1**
	4369	19.3	5003	22.1	**R2**
F2	4880	21.5	5771	25.5	**R2**
	4880	14.3	5771	16.9	**R3**
F3	5508	16.2	6855	20.1	**R3**
	5508	12.1	6855	15	**R4**
F4	6285	13.8	8554	18.8	**R4**
	6285	9.1	6676	9.7	**R12**
F5	4456	38.8	5305	38.8	**R5**
	4456	18.5	5305	22	**R6**
F6	4994	22	6176	27.3	**R6**
	347	1.4	1985	8.2	**R7**
	4848	14.2	4207	12.3	**R8**
F7	5496	16.1	5069	14.9	**R8**
	394	1.6	2390	9.9	**R7**
	5496	16.1	5069	14.9	**R9**
	5496	12.1	5069	11.1	**R11**
F8	6246	13.7	6535	14.3	**R10**
	390	1.6	2417	10	**R7**
	6246	13.7	5535	12.1	**R11**
	6246	9.1	6535	9.5	**R12**

TABLE 6. The overall operational time for all OC relays in scenarios 1 and 2 at IEEE 9 BUS system.

IEEE 9 bus system	Overall operational time for all relays NI	Overall operational time for all relays NTC
Scenario 1	**9.3519**	**8.8475**
Scenario 2	**11.2824**	**10.3534**

TABLE 7. The short-circuit current values (LLL) and operation time OC relays (Mode 1, NI approach).

NI approach										
Fault location	LLL fault (A)					Relays Operational Time (sec) Relays (Primary/Backup)				
F1	R1(P) 1648	R13(B) 1648	R2(P) 4683	R4(B) 4683	-------------	R1(P) 0.332	R13(B) 0.63	R2(P) 0.0215	R4(B) 0.32	------
F2	R4(P) 4683	R6(B) 3510	R15(B) 594	R3(P) 1648	R1(B) 1648	R4(P) 0.32	R6(B) 0.6217	R15(B) 0.628	R3(P) 0.032	R1(B) 0.332
F3	R6(P) 5433	R7(B) 4925	R8(B) 543	R5(P) 3293	R15(B) 920	R6(P) 0.5371	R7(B) 0.837	R8(B) 0.8326	R5(P) 0.291	R15(B) 0.434
F4	R12(P) 10988	R7(B) 8375	R5(B) 2635	R8(P) 923	R11(B) 923	R12(P) 0.02	R5(B) 0.317	R7(B) 0.605	R8(P) 0.5409	R11(B) 0.844
F5	R10(P) 4913	R6(B) 3416	R9(P) 991	R14(B) 991	R15(B) 578	R10(P) 0.021	R6(B) 0.628	R9(P) 0.04	R14(B) 0.34	R15(B) 0.646

TABLE 8. The short-circuit current values (LLL) and operation time of OC relays (Mode 1, NTC approach).

NTC approach										
Fault Location	LLL fault(A)					Relays Operational Time (sec); Relays(Primary/Backup)				
F1	R1(P) 1648	R13(B) 1648	R2(P) 4683	R4(B) 4683	-------------	R1(P) 0.33	R13(B) 0.63	R2(P) 0.0154	R4(B) 0.316	---------
F2	R4(P) 4683	R6(B) 3510	R15(B) 594	R3(P) 1648	R1(B) 1648	R4(P) 0.316	R6(B) 0.6156	R15(B) 0.615	R3(P) 0.03	R1(B) 0.33
F3	R6(P) 5433	R7(B) 4925	R8(B) 543	R5(P) 3293	R15(B) 920	**R6(P) 0.4277**	R7(B) 0.728	R8(B) 0.728	R5(P) 0.265	R15(B) 0.534
F4	R12(P) 10988	R7(B) 8375	R5(B) 2635	R8(P) 923	R11(B) 923	R12(P) 0.01	R7(B) 0.304	R7(B) 0.594	R8(P) 0.6107	R11(B) 0.911
F5	R10(P) 4913	R6(B) 3416	R9(P) 991	R14(B) 991	R15(B) 578	R10(P) 0.0148	R6(B) 0.627	R9(P) 0.04	R14(B) 0.337	R15(B) 0.62

TABLE 9. The short-circuit current values (LG-1) and operation time of OC relays (Mode 1, NI approach).

NI approach										
Fault location	LG-1 fault (A)					Relays Operational Time (sec) Relays (Primary/Backup)				
F1	R1(P) 2584	R13(B) 2584	R2(P) 2490	R4(B) 2490	-------------	R1(P) 0.291	R13(B) 0.59	R2(P) 0.0271	R4(B) 0.327	---------
F2	R4(P) 3882	R6(B) 2305	R15(B) 576	R3(P) 1912	R1(B) 1912	R4(P) 0.277	R6(B) 0.5777	R15(B) 0.577	R3(P) 0.03	R1(B) 0.33
F3	R6(P) 4458	R7(B) 3909	R8(B) 556	R5(P) 4393	R15(B) 1114	R6(P) 0.4519	R7(B) 0.752	R8(B) 0.752	R5(P) 0.133	R15(B) 0.34
F4	R12(P) 4481	R7(B) 3775	R5(B) 709	R8(P) 2805	R11(B) 2805	R12(P) 0.02	R5(B) 0.322	R7(B) 0.775	R8(P) 0.2864	R11(B) 0.587
F5	R10(P) 3355	R6(B) 2173	R9(P) 2896	R14(B) 2896	R15(B) 543	R10(P) 0.02413	R6(B) 0.5923	R9(P) 0.03	R14(B) 0.33	R15(B) 0.615

TABLE 10. The short-circuit current values (LG-1) and operation time of OC relays (Mode 1, NTC approach).

NTC approach										
Fault location	LG-1 fault(A)					Relays Operational Time (sec) Relays(Primary/Backup)				
F1	R1(P) 2584	R13(B) 2584	R2(P) 2490	R4(B) 2490	--------	R1(P) 0.279	R13(B) 0.58	R2(P) 0.024	R4(B) 0.324	---------
F2	R4(P) 3882	R6(B) 2305	R15(B) 576	R3(P) 1912	R1(B) 1912	R4(P) 0.243	R6(B) 0.543	R15(B) 0.543	R3(P) 0.028	R1(B) 0.328
F3	R6(P) 4458	R7(B) 3909	R8(B) 556	R5(P) 4393	R15(B) 1114	R6(P) 0.3496	R7(B) 0.65	R8(B) 0.6497	R5(P) 0.126	R15(B) 0.436
F4	R12(P) 4481	R7(B) 3775	R5(B) 709	R8(P) 2805	R11(B) 2805	R12(P) 0.02	R5(B) 0.316	R7(B) 0.657	R8(P) 0.3285	R11(B) 0.629
F5	R10(P) 3355	R6(B) 2173	R9(P) 2896	R14(B) 2896	R15(B) 543	R10(P) 0.019	R6(B) 0.5603	R9(P) 0.02	R14(B) 0.32	R15(B) 0.553

relay operational time compared to the NTC approach. For instance, the R6(P) recorded 0.5371 Sec for F3 by using the NI approach compared to 0.4277 Sec for the NTC approach.

The employment of the Nonstandard Tripping Characteristic (NTC) approach helped to significantly decrease the relay operational time for LLL fault, as shown in Tables 5 and 6.

TABLE 11. **The OC relays operation time for NI and NTC approaches (Mode 2, LLL fault scenario).**

Fault location	Relays Operational Time (sec) Relays(Primary/Backup)					Relays Operational Time (sec) Relays(Primary/Backup)				
	NI					NTC				
F1	R1(P) 0.32	R13(B) 0.6	R2(P) 0.0239	R4(B) 0.357	---------	R1(P) 0.317	R13(B) 0.61	R2(P) 0.0196	R4(B) 0.401	---------
F2	R4(P) 0.321	R6(B) 0.6211	R15(B) 0.663	R3(P) 0.033	R1(B) 0.34	R4(P) 0.317	R6(B) 0.6144	R15(B) 0.625	R3(P) 0.03	R1(B) 0.336
F3	R6(P) 0.5371	R7(B) 0.837	R8(B) 0.8326	R5(P) 0.283	R15(B) 0.451	R6(P) 0.4277	R7(B) 0.728	R8(B 0.7278	R5(P) 0.251	R15(B) 0.544
F4	R12(P) 0.02	R5(B) 0.32	R7(B) 0.605	R8(P) 0.5409	R11(B) 0.844	R12(P) 0.01	R5(B) 0.308	R7(B) 0.594	R8(P) 0.6107	R11(B) 0.911
F5	R10(P) 0.0226	R6(B) 0.6265	R9(P) 0.04	R14(B) 0.34	R15(B) 0.681	R10(P) 0.0149	R6(B) 0.6248	R9(P) 0.04	R14(B) 0.34	R15(B) 0.63

TABLE 12. **The OC relays operation time for NI and NTC approaches (Mode 3, LLL fault scenario).**

Fault location	Relays Operational Time (sec) Relays(Primary/Backup)					Relays Operational Time (sec) Relays(Primary/Backup)				
	NI					NTC				
F1	R1(P) 0.301	R13(B) 0.56	R2(P) 0.0238	R4(B) 0.354	---------	R1(P) 0.298	R13(B) 0.58	R2(P) 0.0194	R4(B) 0.397	---------
F2	R4(P) 0.319	R6(B) 0.6233	R15(B) 0.631	R3(P) 0.031	R1(B) 0.321	R4(P) 0.312	R6(B) 0.6187	R15(B) 0.616	R3(P) 0.029	R1(B) 0.319
F3	R6(P)	R7(B) 0.837	R8(B) 0.833	R5(P) 0.294	R15(B) 0.391	R6(P) 0.4269	R7(B) 0.728	R8(B 0.7278	R5(P) 0.27	R15(B) 0.505
F4	R12(P) 0.02	R5(B) 0.405	R7(B) 0.889	R8(P) 0.5165	R11(B) 0.799	R12(P) 0.01	R5(B) 0.402	R7(B) 0.748	R8(P) 0.5951	R11(B) 0.889
F5	R10(P) 0.021	R6(B) 0.63	R9(P) 0.04	R14(B) 0.34	R15(B) 0.562	R10(P) 0.0145	R6(B) 0.6321	R9(P) 0.04	R14(B) 0.34	R15(B) 0.594

TABLE 13. **The OC relays operation time for NI and NTC approaches (Mode 3, LG-1 fault scenario).**

Fault location	LG fault(A)					Relays Operational Time (sec) Relays(Primary/Backup)				
	NI					NTC				
F1	R1(P) 0.26	R13(B) 0.51	R2(P) 0.027	R4(B) 0.327	---------	R1(P) 0.232	R13(B) 0.51	R2(P) 0.0239	R4(B) 0.323	---------
F2	R4(P) 0.274	R6(B) 0.5834	R15(B) 0.442	R3(P) 0.028	R1(B) 0.3	R4(P) 0.238	R6(B) 0.5499	R15(B) 0.496	R3(P) 0.025	R1(B) 0.292
F3	R6(P) 0.4507	R7(B) 0.747	R8(B) 0.7454	R5(P) 0.133	R15(B) 0.283	R6(P) 0.3472	R7(B) 0.648	R8(B) 0.648	R5(P) 0.111	R15(B) 0.383
F4	R12(P) 0.02	R5(B) 0.302	R7(B) 0.774	R8(P) 0.2853	R11(B) 0.584	R12(P) 0.02	R5(B) 0.308	R7(B) 0.657	R8(P) 0.3265	R11(B) 0.625
F5	R10(P) 0.024	R6(B) 0.6009	R9(P) 0.03	R14(B) 0.32	R15(B) 0.469	R10(P) 0.01918	R6(B) 0.5701	R9(P) 0.02	R14(B) 0.32	R15(B) 0.507

Therefore, the sensitivity of the protection model by using the NTC approach is sufficiently provided and improved compared to the NI approach. In addition, all tripping times for OC relays satisfied the protection model constraints when the NTC approach was used.

Similarly, Tables 9 and 10 present the short-circuit currents for Line to Ground fault (LG-1) and the OC relays operational time for each relay (R1 to R15) in different fault locations for NI and NTC approaches. The NI approach registered delays in the tripping time compared to the NTC approach. For example, the primary relays R10 registered 0.02413 Sec by using the NI approach compared to 0.019 Sec for the NTC approach for F5. As shown in Tables 9 and 10, the tripping time of all relays is significantly decreased when the NTC approach is used. For example, the NTC approach decreased the primary relay R6 at F3 by 22.5% compared to the NI approach. The R7 will act as a backup relay for R6 at F3 (LG-1) and will operate at 0.65 Sec and 0.752 Sec for NTC and NI approaches, respectively. Therefore, the NTC approach improved the sensitivity term compared to the NI approach.

2) MODEL 2 TEST RESULTS

To evaluate the impacts of increasing the DGs such as wind generation units on the OC relays coordination problem and

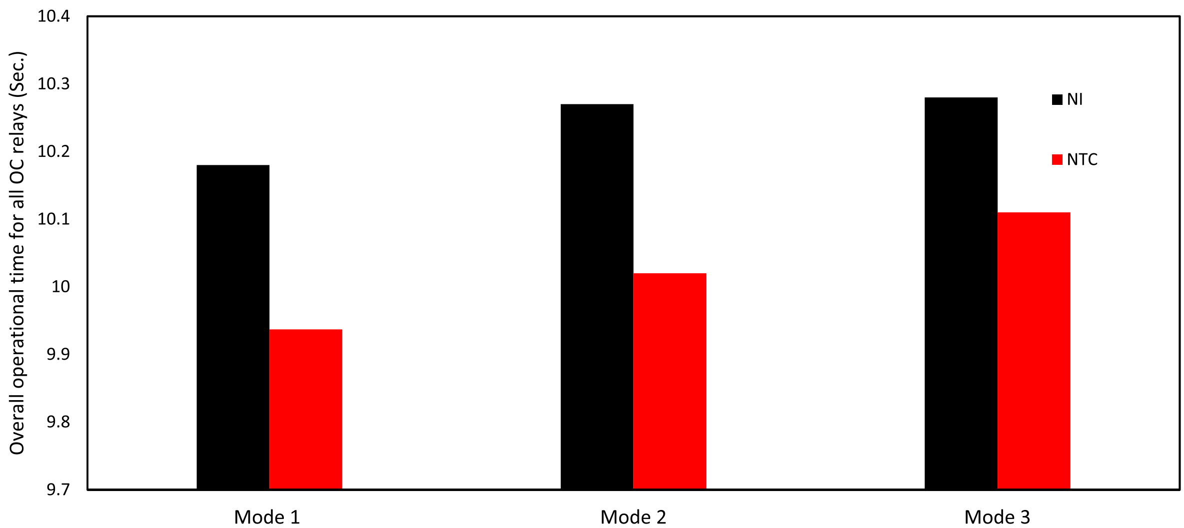


FIGURE 10. The overall operational time for all OC relays in Modes 1, 2, and 3 (LLL fault).

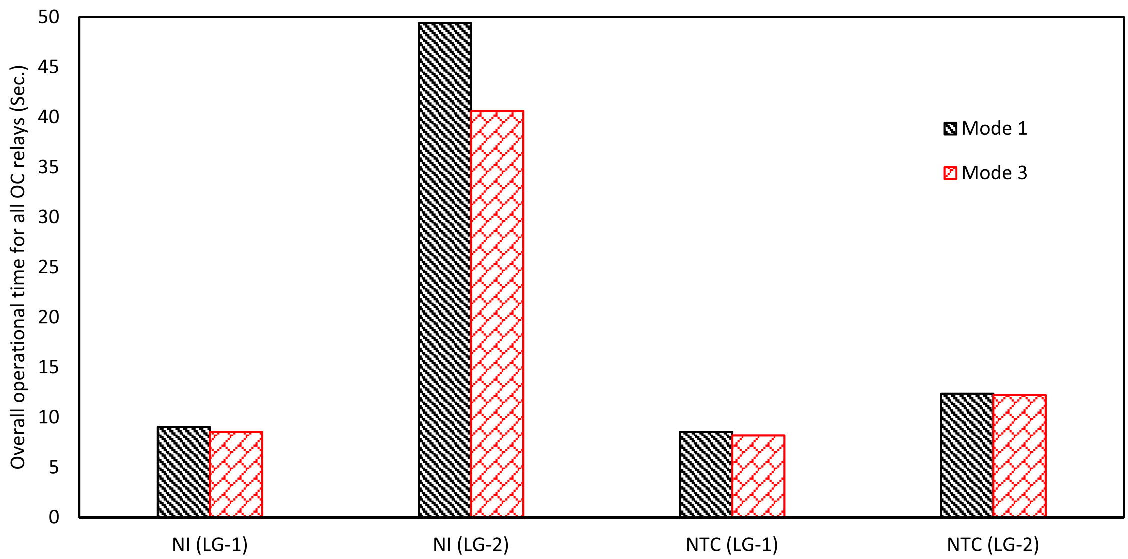


FIGURE 11. The overall operational time for all OC relays in Modes 1 and 3 (LG-1 and LG-2 faults).

solvers, Model 2 with a 25% increase in the capacity of DGs is presented in this subsection. The operational time for the OC relays (primary and backup) by using NI and NTC approaches at different LLL faults locations is reported in Table 11. The NTC approach outperformed the benchmark NI approach in terms of tripping time for all faults. The tripping time for all relays by using NTC was reduced compared to the NI approach, as shown in Table 11. For example, the operational time for the primary relay, R12, was decreased from 0.02 Sec (NI approach) to 0.01 Sec (NTC approach) for F4. As shown in Table 11, the operational tripping time for the primary relays R6, R12 and R10 at faults F3, F4 and F5 is significantly decreased for using NTC by 20.4%, 50% and 34.1%, respectively, compared to the NI approach. The decrease in the operational tripping time of relays using the NTC approach could help to increase the stability of the network and reduce the overall operation time of relays.

3) MODE 3 TEST RESULTS

The performance of NTC and NI characteristics, as coordination criteria, are evaluated and examined on the IEC microgrid system with a 50% increasing the DGs. This subsection aims to investigate the high level of increment of DGs (50%) on the OC coordination problem and the tripping time of relays. Tables 12 and 13 present the tripping time for all OC relays for Three-Phase fault (LLL) and Line to Ground fault (LG-1) in different fault locations. In this model, the primary R6 during F3 fault (LLL) operated at 0.4269 Sec and 0.5368 Sec for NTC and NI approaches, respectively.

TABLE 14. The main parameters of the optimization algorithms.

Algorithm	Parameters	Optimal value	Testing Range
PSO [19,26]	Inertia coefficient inertia	Decreasing from 0.9 to 0.4 (linearly)	----
	Number of search agents	100	50-300
	Maximum number of iterations	1000	100-2000
	Acceleration coefficient	1 and 2	
MPSO [26,27]	Inertia coefficient inertia	Decreasing from 0.9 to 0.4 (linearly)	----
	Number of search agents	100	50-300
	Maximum number of iterations	1000	100-2000
	Acceleration coefficient	1 and 2	
MFO [1,30]	Population size	100	50-300
	Maximum number of iterations	1000	100-2000
GWO [1,29]	Population size	100	50-300
	Maximum number of iterations	1000	100-2000
TL [28]	Size of population	100	50-300
	Maximum iteration number	1000	100-2000

TABLE 15. The proposed optimization algorithms results (TMS and total tripping time) for LLL fault scenario.

Relay NO.	PSO		MPSO		TL		GWO		MFO	
	NI	NTC	NI	NTC	NI	NTC	NI	NTC	NI	NTC
R1	0.1023	0.116	0.10231	0.1116	0.102311	0.111592	0.10231	0.11152	0.10229	0.11149
R2	0.01	0.01	0.0100	0.01	0.01	0.01	0.01	0.01001	0.01	0.01001
R3	0.01	0.01	0.010	0.01	0.01	0.01	0.01	0.01001	0.01	0.01
R4	0.1495	0.2045	0.1495	0.2044	0.149499	0.204427	0.149399	0.2039	0.149383	0.20388
R5	0.1198	0.1312	0.1197	0.1310	0.119728	0.131048	0.119728	0.13	0.119719	0.13
R6	0.2619	0.3186	0.2618	0.3185	0.261836	0.318513	0.261827	0.3185	0.261821	0.3187
R7	0.1713	0.1869	0.1712	0.1868	0.171226	0.186845	0.171146	0.1868	0.171146	0.1866
R8	0.1206	0.1635	0.12062	0.1634	0.12062	0.163441	0.12062	0.1634	0.12058	0.1635
R9	0.01	0.01	0.01	0.0100	0.01	0.01	0.01	0.0101	0.01001	0.01
R10	0.01	0.01	0.01	0.0100	0.010001	0.01	0.01	0.01	0.01	0.0101
R11	0.1547	0.2227	0.1546	0.2226	0.154668	0.22262	0.1546	0.2229	0.1547	0.2229
R12	0.01	0.01	0.01	0.0100	0.01	0.01	0.01	0.01	0.01	0.01
R13	0.1419	0.1695	0.1418	0.1692	0.141828	0.169229	0.141832	0.1694	0.141834	0.16933
R14	0.0665	0.0843	0.066	0.0843	0.066473	0.084311	0.06647	0.0841	0.06644	0.0843
R15	0.09	0.1380	0.0890	0.1380	0.089076	0.13802	0.08903	0.13801	0.089056	0.1379
Overall operational time	10.1894	9.939	10.169	9.934	10.169	9.935	10.1673	9.929	10.1669	9.928

The R7 will act as a backup relay for R6 at F3 (LLL) and will operate at 0.728 Sec and 0.837 Sec for NTC and NI approaches, respectively. The operation time for relays (R1 to R15) was reduced by using NTC compared to the NI approach for LG fault, as shown in Table 13. For example, the tripping time for the primary relay, R10, was decreased by 20.1% for using the NTC approach compared to NI at F5. The R6 will operate as the backup relay for R10 at F5 (LG-1)

TABLE 16. The proposed optimization algorithms results (TMS and total tripping time) for LG-1 fault scenario.

Relay NO.	PSO		MPSO		TL		GWO		MFO	
	NI	NTC	NI	NTC	NI	NTC	NI	NTC	NI	NTC
R1	0.108981	0.119019	0.109	0.119012	0.109	0.119	0.108	0.118	0.1082	0.119
R2	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0101	0.0101	0.0101
R3	0.01	0.01	0.01	0.01	0.01	0.01	0.0101	0.01	0.01	0.0101
R4	0.120872	0.135211	0.121	0.135209	0.1209	0.135	0.1208	0.134	0.12091	0.135
R5	0.058916	0.077237	0.059	0.077224	0.0589	0.077	0.0587	0.076	0.0586	0.074
R6	0.206756	0.217222	0.207	0.217134	0.2067	0.217	0.2069	0.2172	0.2073	0.2171
R7	0.128386	0.154434	0.128	0.154391	0.1283	0.154	0.1283	0.153	0.1284	0.153
R8	0.110965	0.146993	0.111	0.146916	0.111	0.147	0.111	0.147	0.11	0.1471
R9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.001	0.0101	0.001
R10	0.01	0.01	0.01	0.01	0.01	0.01	0.0101	0.01	0.01	0.0101
R11	0.204115	0.242827	0.204	0.242703	0.204	0.243	0.206	0.243	0.206	0.243
R12	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0101
R13	0.171758	0.186347	0.171	0.186238	0.1715	0.186	0.1713	0.186	0.1714	0.186
R14	0.115089	0.126328	0.11	0.126235	0.115	0.126	0.113	0.126	0.114	0.126
R15	0.080105	0.120644	0.08	0.12063	0.0801	0.121	0.0801	0.121	0.08011	0.123
Overall operational time	9.0318	8.5229	9.0309	8.5202	9.0294	8.5202	9.023	8.4769	9.0222	8.5008

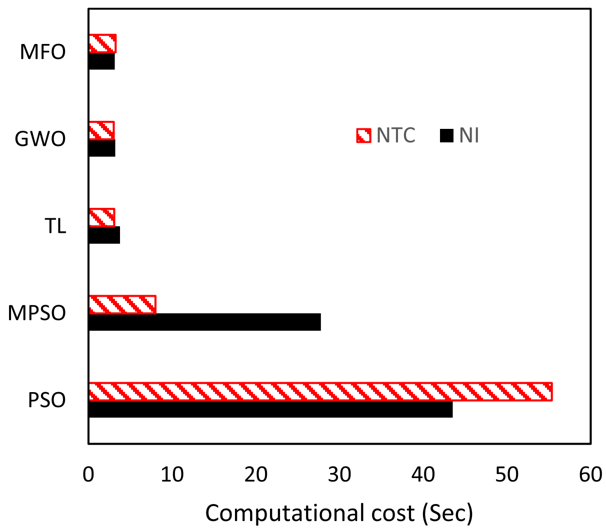


FIGURE 12. Comparison of computational costs results for the proposed optimization algorithms (Mode 1, LLL fault scenario).

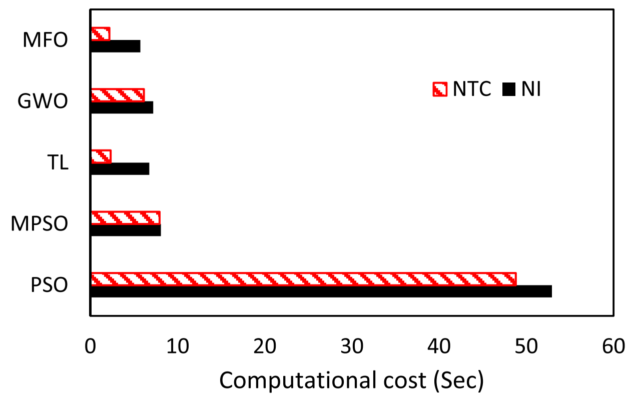


FIGURE 13. Comparison of computational costs results for the proposed optimization algorithms (Mode 1, LG-1 fault scenario).

with 0.5701 Sec and 0.6009 Sec for NTC and NI approaches, respectively. The NTC approach decreased the operational tripping time of relays, which could help to increase the stability of the network and reduce the overall operation time of relays.

4) DISCUSSION AND COMPARISON

This section aims to summarize and compare the performance of proposed NTC and NI approaches over the three proposed operation modes. The overall operational time for all OC relays in Modes 1, 2 and 3, as shown in Fig.10, was computed using the PSO algorithm for LLL fault. The results in previous subsections show that the NTC approach reduced the overall tripping time of all OC relays for all network modes compared to the NI approach. For example, the overall tripping time in Mode 1 was 10.18 Sec and 9.937 Sec for NI and NTC approaches, respectively. Furthermore, the maximum and minimum reduction in the overall tripping time was 2.5% and 1.7% associated with the NTC approach compared to NI in Mode 2 and 3, respectively. In addition, the results showed that the increase of DGs in the network (Modes 2 and 3) increased the total tripping time for both NI and NTC compared to Mode1.

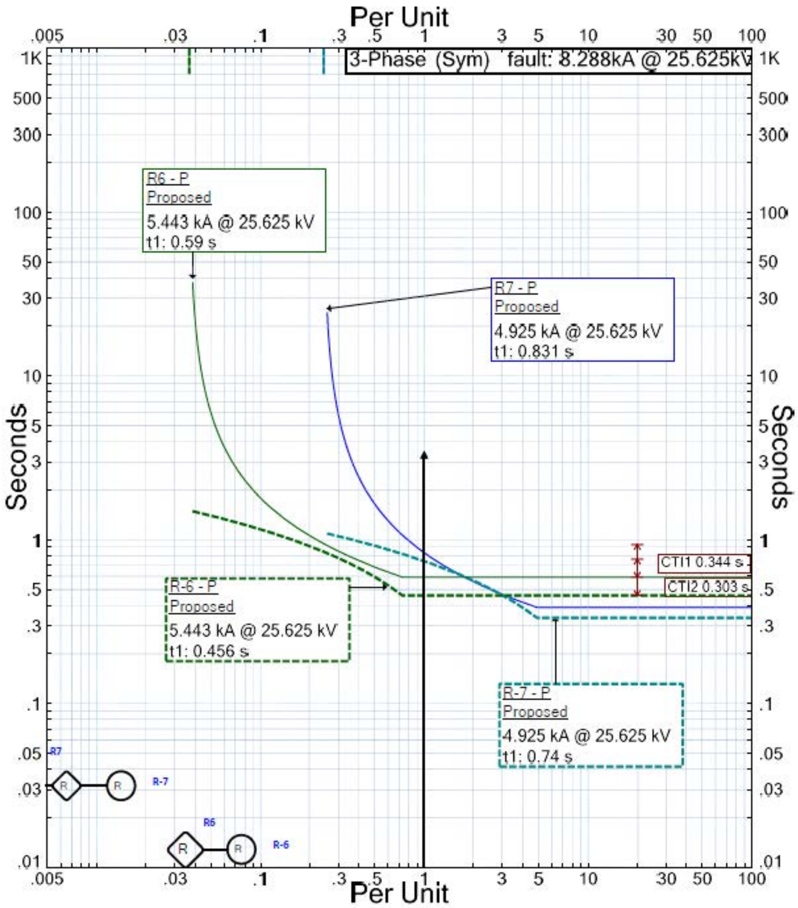


FIGURE 14. Characteristics curves (NTC and NI) of OC relays (R6 and R7) when F3 (LLL) occurred at Mode 1.

5) COMPARISON OF OC RELAYS COORDINATION SCHEMES BASED ON HIGH FAULT RESISTANCE IN TERMS OF SENSITIVITY

In this subsection, different types of LG faults with ground fault impedance equal to 0 and 5 ohms (LG-1 and LG-2, respectively) are taken into consideration to evaluate the performance of NTC and NI approaches. This analysis aims to show the ability of both approaches (NTC and NI) on working with different fault levels. In this section, obtained results for NTC and NI approaches are analyzed in Fig.11 for Mode 1 and Mode 3. In general, the employing of the NTC approach decreased the total tripping time for both fault scenarios (LG-1 and LG-2) in Mode 1 and 3 compared to the traditional approach (NI). For example, the total tripping time in Mode 1 and 3 with LG-2 fault for the NTC approach was 12.36 Sec and 12.22 Sec, respectively, compared to 49.4 Sec and 40.61 Sec for the NI approach. This showed that the NI approach did not work where it took up to 41 and 50 Sec as overall operational relays time when the ground fault impedance equals 5 ohms for Mode 3 and Mode 1, respectively. The NTC showed better results and it operated during LG-2 fault with a total tripping time of up to 13 Sec for Mode 1 and 2. On the other hand, the NTC approach reduced the overall operational relays time for LG-1 fault by 75% and 70%, respectively for Mode 1 and 3. Furthermore, the results showed that both approaches (NTC and NI) obtained a lower tripping time for Mode 3 (with increasing the capacity of DGs by 50%) compared to the standard IEC microgrid (Mode 1).

D. COMPARATIVE PERFORMANCE FOR DIFFERENT METAHEURISTIC OPTIMIZATION ALGORITHMS

In the previous section, the evaluation and performance of the NI and NTC approaches over different faults and power network scenarios are presented. The optimization techniques can play a significant role in improving the performance of the proposed protection scheme model. In this section, a comparison analysis for the new optimal algorithms (MPSO, TL, GWO and MFO) and PSO as common algorithm are presented, in terms of overall operational time for all relays and the computational cost for solving the optimal coordination problem over different fault scenarios for Mode 1. The parameters of the optimization algorithms (MPSO, TL, GWO, MFO and PSO) are selected in this work by examining each parameter over a wide range of

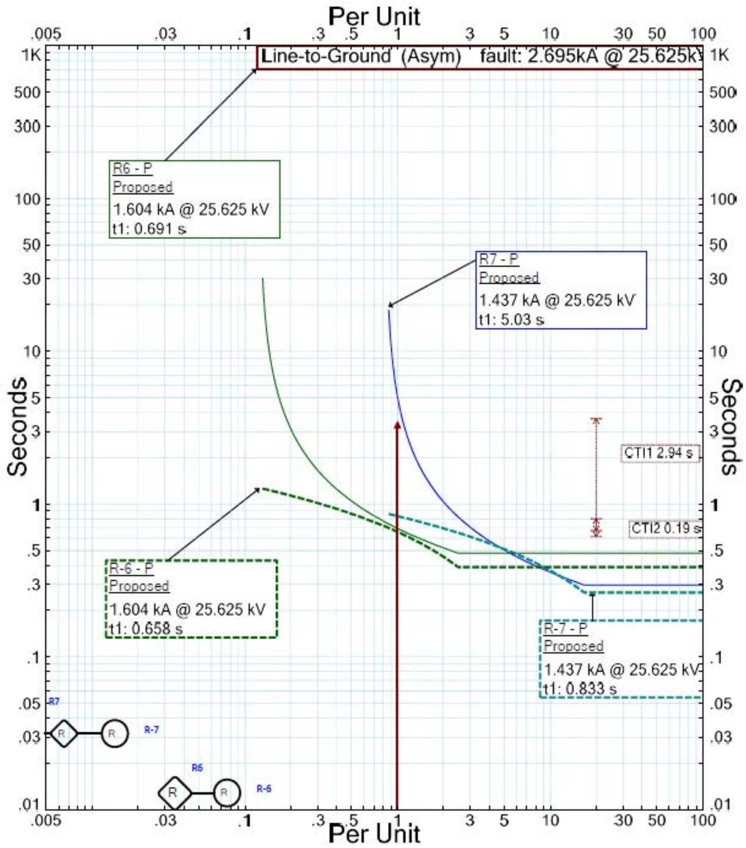


FIGURE 15. Characteristics curves (NTC and NI) of OC relays (R6 and R7) when F3 (LG-2) occurred at Mode 1.

values. Table 14 showed the main optimization parameters, the testing range and the optimal (best) value which been used to obtain the results in this article. In addition, the initial OC relays setting for solving the coordination optimization problem are randomly chosen within the allowable limits.

To examine and evaluate the performance of the NTC and NI approaches over different fault scenarios (LLL and LG-1), the proposed optimization algorithms (MPSO, TL, GWO, MFO and PSO) have been employed to find the optimal TMS value and minimize the total tripping time for all OC relays. Tables 15 and 16 presented the TMS values and total tripping time for all OC relays for the proposed optimization algorithms by considering NTC and NI approaches and the fault scenarios (LLL and LG-1, respectively). The superiority of the NTC approach in solving complex coordination problems, as discussed in Section 2, helped to reduce the total tripping time of all OC relays compared to the NI approach over LLL and LG-1 fault scenarios for all optimization algorithms. For example, the MPSO and TL reduced the tripping time of LLL fault from 10.169 Sec for NI to 9.934 Sec and 9.935 Sec, respectively, for the NTC approach. The minimum total tripping time of LLL fault for NI and NTC approaches was obtained by MFO with 10.1669 Sec and 9.928 Sec, respectively. The PSO algorithm recorded the maximum total tripping time of LLL for the NI and NTC approach with 10.1894 Sec and 9.939 Sec, respectively. Table 16 showed that the total tripping time of LG-1 was lower than the LLL fault scenario for all optimization algorithms. Similar to the LLL fault scenario, the NTC reduced the total tripping time of all OC relays compared to the NI approach over LG-1 fault scenarios. For example, the GWO and PSO algorithm minimized the tripping time of LG-1 fault from 9.023 Sec and 9.0318 Sec for NI to 8.4769 Sec and 8.5229 Sec, respectively, for the NTC approach. The minimum total tripping time of LG-1 fault for NI and NTC approaches was obtained by MFO and GWO with 9.0222 Sec and 8.4769 Sec, respectively.

1) COMPARISON OF OC RELAYS COORDINATION SCHEMES IN TERMS OF COMPUTATIONAL COSTS

In this work, the computational cost is the required time (execution time) for solving the optimization problem of OC relays coordination by using the proposed optimization algorithms. The average computational cost for solving OC relays coordination problem in the IEC network (Mode 1) by using different optimization algorithms (MPSO, TL, GWO, MFO and PSO) and considering LLL and LG-1 scenarios are presented in Fig.12 and Fig.13, respectively. The average computational costs in this section have been calculated for

100 independent trials on a 2.8-GHz i7 PC with 16 GB of RAM. In general, the new metaheuristic optimization algorithms (MFO, GWO, TL and MPSO) outperformed the common algorithm in terms of minimum computational costs for both fault scenarios. In the LLL fault scenario with the NI approach, the MFO, GWO and TL reduced the computational costs by 92.7%, 92.6% and 91.3% compared to PSO. The minimum reduction for LLL fault scenario with NI approach was for MPSO algorithm by recording time equal to 27.78425 Sec compared to 43.5262 Sec for PSO. This is related to the fact that the MFO, GWO and TL algorithms required a few parameters compared to PSO and MPSO which makes them easier to implement. In addition, the NTC recorded a lower computational cost compared to NI in all optimization algorithms except the PSO and MFO algorithms. However, the NTC approach outperformed the NI in all optimization algorithms for the LG-1 fault scenario, as shown in Fig.13. In addition, the MPSO obtained better results in the LG-1 fault scenario compared to the LLL scenario.

E. EVALUATION OF THE NTC AND NI APPROACHES USING INDUSTRIAL SOFTWARE (ETAP)

ETAP is one of the common and powerful tools in the power protection field with an easy-to-use interface. As standard computer software, ETAP, is used to simulate, evaluate and examine the efficiency and feasibility of the different power operational approaches considering the network parameters and relays setting. In this article, the ETAP program has been employed to generate and evaluate the proposed optimal coordination of OC relays schemes in the IEC network without any miss-operation or miss-coordination. In this section, the performance of the NTC and NI curves are examined and evaluated for different faults (LLL and LG-2) and different operation Scenarios (Mode1 and Mode 3). In this work, the argument of the difficulties in achieving optimal OC relays coordination with standard approaches or using NI schemes is discussed and presented in Section 2. Therefore, the ETAP simulation model developed in this section demonstrates and evaluates the proposed OC relays coordinate schemes. Fig.13, Fig.14 and Fig.15 presented the ETAP package results including the pre-setting for relays and the time-current characteristics (NTC and NI). In addition, Fig.13 to Fig.15 presented the graphs of NTC and NI curves and simulated the coordination between primary and backup OC relay pairs. Fig.13 presented the coordination between OC relays (R6 and R7) when F3 (LLL) occurred in Mode 1. The R6 as the primary relay will be firstly operated and the R7 as the backup relay will be sequentially operated when a failure happens in R6, as shown In Fig 13. The coordination time, CTI, between the primary and backup OC relays is simulated in ETAP as a marginal time level based on the IEEE-242 where the CTI is between 0.2 and 0.5 Sec. Fig.13 showed that the NTC approach outperformed the NI approach in terms of minimum tripping time, where R6 will be operated in 0.456 Sec and 0.59 Sec (as primary) for NTC and NI, respectively, while R7 will be

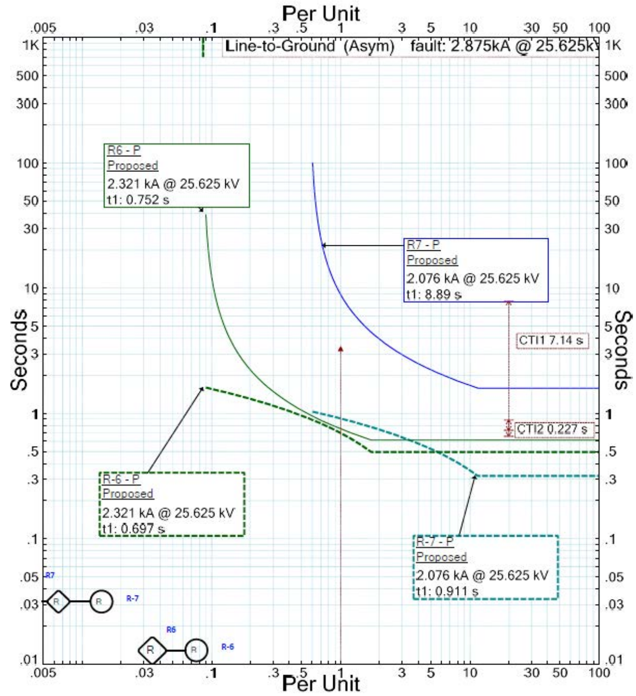


FIGURE 16. Characteristics curves (NTC and NI) of OC relays (R6 and R7) when F3 (LG-2) occurred at Mode 3.

operated as a backup in 0.74 Sec and 0.831 Sec for NTC and NI, reactively. However, both approaches (NTC and NI) successfully operated concerning the CTI time.

To evaluate the impact of applying different types of fault, Fig.14 presented the coordination between R6 and R7 for the line to ground fault with resistance equal to five ohms (LG-2) at Mode1. Both approaches (NTC and NI) successfully operated concerning the constraints of the CTI time. However, the NTC approach recorded a lower tripping time compared to the NI approach for both primary and backup relays. The tripping time for R6 as primary was 0.658 Sec and 0.691 Sec for NTC and NI, respectively, while the backup relay (R7) was 0.833 Sec and 5.03 Sec for NTC and NI, respectively.

Finally, the coordination for OC relays in Mode 3 (with a 50% increment in the capacity of renewable energy in the IEC network) is tested and evaluated for both approaches NTC and NI with LG-2 fault scenarios. The ETAP graphical representation of OC relays coordination schemes (NTC and NI) is shown in FIGURE 15. Similarly, to the previous two cases, the NTC and NI approaches successfully operated concerning the constraints of the CTI time and the NTC approach outperformed the NI approach in terms of minimum tripping time. The tripping time for R6 as primary was 0.697 Sec and 0.752 Sec for NTC and NI, respectively, while the backup relay (R7) was 0.911 Sec and 8.89 Sec for NTC and NI, respectively. In general, the results in Fig.13, Fig.14 and Fig.15 by using ETAP showed a significant reduction and minimization in the relays tripping time (primary and backup) for using NTC approaches compared to NI, and consequently less overall tripping time for the system. In microgrid networks or power networks with renewable energy resources, it is significant to immediately disconnect (very fast response) faulty parts of the grid. The highly sensitive and fast protection scheme, NTC, aims to reduce and avoid damages (equipment and human life) in the grid and improve the reliability of the system.

V. CONCLUSION

This work showed that the conventional OC relays coordination approaches face many challenges and might not be suitable to guarantee sensitivity and selectivity in microgrid systems. Therefore, this paper introduced a fast-response OC relays scheme based on nonstandard tripping characteristics, NTC, and metaheuristic optimization algorithms (MPSO, TL, GWO and MFO). The proposed NTC approach outperformed the standard tripping characteristic, NI, in terms of the total tripping time and coordination time. MPSO, TL, GWO and MFO techniques were developed for solving the OC relays coordination problem and compared to the common technique from the literature, PSO. All of the proposed new metaheuristic optimization algorithms provided higher quality performance in terms of total tripping time and the computational cost during different types of faults and microgrid operation modes. A comparison was carried out with different fault scenarios and levels of renewable energy resources in the network, to investigate the impact of increasing the capacity of DGs in a microgrid protection scheme. The results showed that the increase of DGs in the network (Modes 2 and 3) increased the total tripping time for both NI and NTC compared to Mode1.

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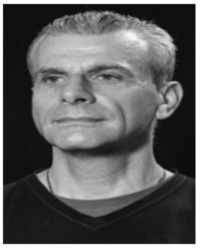

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