University of Chester

Optimization of Nonstandard Tripping Protection Scheme for Radial and Meshed Power Networks with Distributed Generation Systems

These are submitted in accordance with the requirements of the University of Chester for the degree of Doctor of Philosophy by

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Declaration

I confirm that this is my own work and none of the works described in this thesis were submitted in support of applications for other degrees or qualifications of this or another learning institution. Whereas several materials parts of the present thesis have been published during the PhD journey.

Salima Abeid

Abstract

The operation of modern distribution networks (DNs) tackles serious challenges due to the integration of distributed generations (DGs). The protection scheme is one of these challenges. Particularly, the occurrence of bi-directional short-circuit current flow that affects the reliability, sensitivity and selectivity of traditional overcurrent relays (OCRs). In addition, the future distribution system with DGs is expected that will be occupied by the meshed networks alongside the classical radial design and alternating between the grid-connected and islanded mode, for enhancing their reliability.

The purpose of the present thesis is to introduce practicable protection proposals for such implementations and address pertinent protection issues. In this context, a comprehensive literature review has been introduced in the present thesis critically. The main contribution of this thesis is the introduction of advanced non-standard methods for addressing the coordination problem of OCRs in DNs with a growing integration of DGs in the power system.

Firstly, this thesis presents a novel optimal OCR coordination scheme developed using the non-standard current characteristics (NSTCCs) approach. This approach is specifically designed to adjust OCRs. The proposed equation is contingent on a variable dynamic coefficient based on a logarithmic function curve for improving the flexibility of the curve, thus the optimal coordination between OCRs has been obtained throughout different fault modes. For enhancing the performance of the proposed approach on the OCRs coordination in the DNs, two optimization techniques, namely, the genetic algorithm (GA) and hybrid gravitational search algorithm–sequential quadratic programming (GSA-SQP) have been employed. Moreover, Due to the proposed equation including only one variable coefficient, the NSTCCs has efficaciously contributed to reducing the number of constraints to eliminate significant constraints numbers in the coordination between the overcurrent protective relays. Radial networks, including IEEE 9-bus and IEC MG systems as benchmark as well as meshed networks, namely, IEEE 9 and 30-bus systems have been used to test the proposed protection scheme. The results of the proposed optimal OCRs coordination scheme have been compared to standard and nonstandard characteristics reported in the literature. The results showed a significant improvement in terms of the protection system selectivity and reliability by minimizing the operating time (OT) of OCRs, ensuring the coordination between primary and backup relays and demonstrating the effectiveness of the proposed method throughout minimum and maximum fault modes.

For radial networks based on GA, the reduction percentages of tripping time by using NSTCCs for IEC MG benchmark without DGs (mode 1), DN with DGs (mode 2) and islanded mode (mode 3) compared to the lowest OT value obtained from literature are 42.24%, 60% and 54.74%, respectively. In addition, for the IEEE9-bus radial network, the comparison is between the proposed NSTCCs, standard current characteristics (STCCs) and nonstandard scheme (NSS) recorded in the literature. The overall OT of proposed NSTCCs on mod 1, mode 2 and mode 3 is reduced by 12.06%, 17.33% and 13.55%, respectively compared to STCCs, while it is reduced by 7.05%, 9.91% and 11.42%, respectively compared to NSS. For meshed networks based on the hybrid GSA–SQP algorithm, the NSTCC approach improves the coordination interval time (CTI) between the primary and backup relays. For IEEE 9-bus system meshed network, the sum of CTI values is reduced compared to the sum of CTI values in ref from literature by 16.87%. The OT of proposed NSTCCs is reduced by 78.97% compared to STCC and 21.33% compared to NSS. Furthermore, the NSTCC decreased the total OT in the meshed 30-bus test system by 54.4% and 37.9% compared to the literature methods STCC and NSS, respectively. The suggested NSTCC technique is an important development that could greatly enhance the reliability and selectivity of power systems.

Secondly, this thesis investigates the impact of immoderate fault current owing to the presence of DGs on traditional IEC characteristics. The shape of these characteristics has been adjusted to obtain such characteristics. The non-standard characteristics approach (N-SCA) has been proposed for optimal coordination of OCRs installed in DNs by extending the IEC normal inverse characteristics to fifty plug setting multiplier (PSM). Furthermore, an artificial intelligence hybrid algorithm based on water cycle moth flame optimization (HWCMFO) has been proposed as a new optimization technique in OCRs coordination protection to optimize the maximum PSM limits. Several modes have been implemented and tested with an IEC MG benchmark and carried out in MATLAB and NEPLAN software, the obtained results have illustrated the effectiveness and applicability of N-SCA based on the HWCMFO technique considering the limitation of IEC characteristics. The N-SCA outperforms the conventional approach for various fault locations in the several operational modes.

For mode 1, mode 2 and mode 3, the total OT is reduced by 6.32%, 5.61% and only 0.35%, respectively. Particle swarm optimization (PSO) technique is used for comparative purposes. Using the HWCMFO technique reduced the computing speed compared to PSO by 86.59% for mode 1, 29.69% for mode 2 and 89.18% for islanded mode. Moreover, the best cost function values of the proposed HWCMFO technique is reached at less than the PSO technique for all operational modes. For mode1, mode 2 and mode 3, it is reduced by 74.26%, 63.39% and 65%, respectively. Therefore, it is demonstrated that the presented HWCMFO algorithm is suitable for identifying the global minimum objective function value in the OCR coordination.

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Table of Contents

Table of Figures

Table of Tables

Abbreviations

DNs	Distribution Networks
DGs	Distributed Generations
MGs	Micro-Grids
CB	Circuit Breaker
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
CT	Current Transformer
VT	Voltage Transformer
OCRs	Overcurrent Relays
DOCRs	Directional Overcurrent Relays
CTI	Coordination Time Interval
TDS	Time Dial Setting
TMS	Time Multiplier Setting
PSM	Plug Setting Multiplier
OF	Objective Function
NI	Normal Inverse
VI	Very Inverse
EI	Extremely Inverse
STI	Short Time Inverse
LTI	Long Time Inverse
IEC NI	International Electrotechnical Commission Normal Inverse
T	Tripping Time
OT	Operation Time
Isc	Short-Circuit Current
Ip	Pickup Current
SCs	Standard Characteristics
SCA	Standard Characteristic Approach
NSTCC	Nonstandard Time Current Characteristic
STCC	Standard Time Current Characteristic
NSS	Non-standard Scheme
NSCs	Nonstandard characteristics
N-SCA	Non-standard Characteristic Approach
GA	Genetic Algorithm
GSA-SQP	Gravitational Search Algorithm-Sequential Quadratic Programming
WCA	Water Cycle Algorithm
MFO	Moth Flame Optimization
HWCMFO	Hybrid Water Cycle Moth Flame Optimization
PSO	Particle Swarm Optimization
OT	Operation Time
TCCs	Time–Current Characteristics
RESs	Renewable Energy Sources
IDGs	Inverter-based Distributed Generations
SDGs	Synchronous Distribution Generations
PV	Solar Photovoltaics
DFIG	Doubly Fed Induction Generators

LVRT	Low-Voltage Ride-Through
IDMT	Inverse Definite Minimum Time
CBC	Current Based Characteristics
VBC	Voltage Based Characteristics
CTR	Current Transformer Ratios
PMSG	Permanent Magnet Synchronous Generator
FL	Fault Location
PR	Primary Relay
BU	Backup Relay
CPU	Central Processing Unit

Chapter 1: Introduction

1- Introduction

This thesis investigates the possibility of effectively minimising the impact of Distributed Generations (DGs) on power protection systems and Overcurrent Relays (OCRs) by employing a new nonstandard time–current characteristics approach and different optimization techniques. Specifically, the effects of DGs situated on the OCRs at the IEC benchmark and IEEE-9 bus as radial networks as well as IEEE-9 bus and IEEE-30 bus systems as meshed networks will be explored. In addition, the IEC benchmark is used in the present thesis to test a new optimization technique with considering the of IEC normal inverse curve limitations. The optimal coordination approaches are significant solutions to reduce the tripping time of OCRs and improve the performance of protection systems for a power network equipped with DGs. This chapter briefly introduces the protection of the power system and the rising modern challenges and problems at the Distribution Power Networks (DNs), where the impact of DGs on the overcurrent protection schemes is discussed. The subsequent sections outline the project's aims, the key contribution to knowledge made by this effort, and the problem statement that motivates this research.

1.1 The Protection of the Power System

Conventionally, remote power plants generate most of the electrical power consumed, and consumers receive this power through distribution substations along long transmission lines. Eventually, DNs serve the end consumers by providing them with the electricity they need.

This structure as a generator, transmission and distribution system was the basis of the classical DNs design, and it has several disadvantages, such as high carbon emissions, limited resistance to transmission system faults and failures, as they may lead to the loss of many distribution systems, low efficiency, high fuel costs, less reliable system with high construction costs (Brearley & Prabu, 2017). To avoid these issues, technological advances and government incentives have contributed to the significant integration of the DNs toward the vision of DGs.

Integration of DGs into distribution grids requires a reconsideration of traditional protection systems. Particularly. The bidirectional short-circuit current flow, whereas, under new system conditions, determining appropriate protection settings is required to guarantee the reliability of protection. Further, to increase the reliability of modern DNs, the concept of ring or mesh DN configurations, in addition to conventional radial configurations, has been considered (Celli et al., 2004). Figure 1.1 shows the typical basic structure of a power system with and without

DGs at the distribution level. In Figure 1.1, the black arrow represents the possible short-circuit current flow in the transmission level, the red arrow represents the possible short-circuit current flow in the distribution level without DG and the green arrow represents the possible short-circuit current flow in the distribution level with DG.

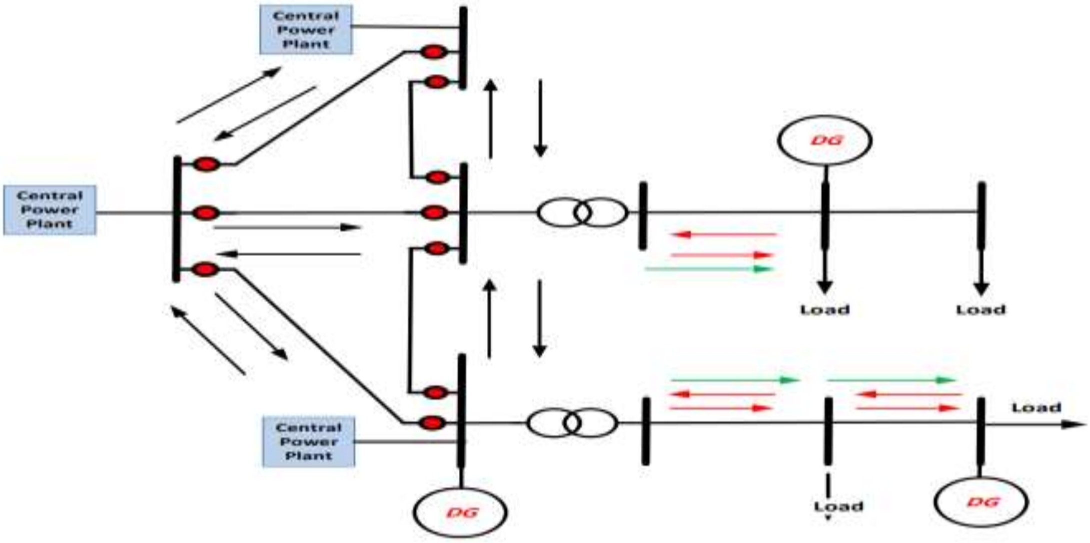


Figure 1.1: A typical power system fundamental structure.

Traditional overcurrent protection schemes protect radial DNs, but the addition of DGs and the increase in the number of connections to DGs have made the concept of protection more difficult. For DGs, which have different modes such as grid-connected and islanded mode, as well as different configurations such as ring and mesh, the existence of new protection schemes is required. Considering factors caused by DGs, such as bidirectional power flow, contributes to the design of alternative protection principles for modern DNs. The purpose of this section is to provide a basic theoretical foundation and an introduction before adopting the protection schemes in the following chapters. Particularly, reviewing some essential aspects of power system protection, including the basic components of the power protection circuit and overcurrent protection principles, which are adopted in the present thesis. In addition, this section outlines the impact of DGs on the protection of DNs, which plays a major role in the design of proposed protection schemes in this thesis.

1.1.1 Essential Aspects of Power System Protection:

The purpose of a power system's protection system is to clear the occurred faults in order to provide a reliable supply without interrupting the majority of consumers, reduce fault damage to the equipment, and maintain people's safety. These changes in the fault current have a significant impact on the basic requirements of the protection system that can be categorized as follows:

- Speed: the protection system's capability to eliminate faults as quickly as possible, minimizing damage caused by faults in the grid or equipment.
- Reliability: The protection system's capability to function correctly, with confidence and dependability, in the face of faults over which it has no control.
- Sensitivity: This is the level of protective relays that will operate the circuit breaker (CB) in abnormal conditions as quickly as possible to avoid equipment damage and sustain stability.
- Selectivity: The protection system's ability to detach a minimum part of the network for fault clearance to guarantee the continuousness of the service for the most potential number of consumers. The present thesis introduces new protection solutions for MGs integrated to DNs that focusing on ensure the selectivity between the protective relays and improve the reliability of the protection system. However, it requires an appropriate technical compromise between sensitivity and selectivity.
- Minimum cost: The goal is to achieve protection targets at the lowest cost.
- Simplicity: The goal is to achieve protection targets using the minimum number of protective equipment.

The major components of a transmission protection system or DN are protective relays. According to the Institute of Electrical and Electronics Engineers (IEEE), a definition of the protective relay is “a device whose function is to detect defective lines or apparatus or other power system of an abnormal or dangerous nature and to initiate appropriate control action” (S. Das, Santoso, & Ananthan, 2021). Relays used for power system protection are classified as electromechanical relays, solid-state relays, digital relays, and numerical relays (Juan M. Gers, Holmes, Institution of, & Technology, 2011).

In this regard, there are other components in the protection system also such as a current transformer (CT) with or without a voltage transformer (VT). The protection equipment from the high AC currents and voltages of the power system can be isolated by these necessary protection transformers. Due to the importance of current measurement in a power system, CT is commonly used and essential, while, voltage measurements are used as a VT for a needed protection scheme like distance, undervoltage and directional overcurrent protection. On the other hand, a VT is needed when the applied protection principle requires voltage. So, the selection of CT or VT ratio based on the protected system. There are two relevant standards for CT ratios: IEEE (13™-, 2016) and International Electrotechnical Commission (IEC) (Transformers—Part, 2007). On the other hand, the primary voltage rating of the VT winding is selected on the basis of the nominal voltage of the protected grid, while, VT secondary voltage ratings are standard, with 100V, 110V, 115V, and 120V being exemplary values in practice (Juan M. Gers et al., 2011).

The protective relay can decide when and whether to fix faults but cannot isolate the faulty parts of the network. Therefore, the CB is an essential component of a protection system. The CB is connected to the protected primary circuit. Once the relay detects a failure, the CB sends a trip command to open and interrupt the circuit. In case of fault occurs, the CB will open and interrupt the circuit when it receives a trip command from the relay (usually within 2 to 5 cycles (Blackburn & Domin, 2006). Depending on the type of fault, the CB can open all three phases or just one phase of the protected circuit. It is obvious that the elements described above are essential components of any power protection circuit. In general, they can be structured as relay, CT / VT and CB, as shown in Figure 1.2 (Blackburn & Domin, 2006).

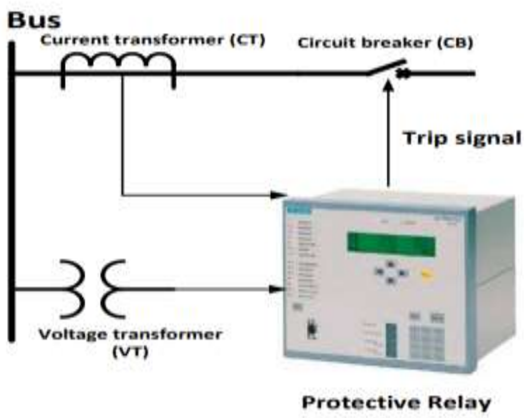


Figure 1.2: Representation of a power protection circuit on a single-line diagram.

There are several types of protective relay that have been used throughout decades for power system protection, namely overcurrent relays (OCR), fuses, reclosers, distance relays, undervoltage relays, and differential relays (Srivastava, Tripathi, Krishan, & Parida, 2018). An OCR is extensively used, and it is considered the most preferable type in the protection system of medium voltage DNs because of their fine selectivity, economical advantages, simplicity, and efficiency in installation and implementation. (Lasseter, 2011)-(Purwar, Vishwakarma, & Singh, 2019). Recently, numerous researchers have developed a variety of optimisation techniques to shorten the relay's operation time and determine the optimal OCR setting. Therefore, addressing the issue of coordination of protection schemes in interconnected DGs is significant (Manditereza & Bansal, 2016)-(M. H. Hussain, Rahim, & Musirin, 2013). However, due to the limited number of commercial protection characteristic curves for different fault scenarios induced by grid-connected DG, the ability of optimization methods to operate quickly is limited.

1.1.2 Overcurrent protection Scheme

The OCRs are used as primary and backup protection, respectively, in the sub transmission and transmission systems (Albasri, Alroomi, & Talaq, 2015). Figure 1.3 illustrates the coordination constraint between the primary and backup relays, in which the horizontal axis represents the location of the fault and the vertical axis represents the time of failure. As ordinarily in a coordination approach, the fault is first isolated by using the primary OCR (R_1). If R_1 fails to operate, the fault is isolated using the backup OCR (R_2) after a time interval known as the coordination time interval (CTI), which is shown in Figure 1.3 between the green and red curves (Rizk-Allah & El-Fergany, 2021). It considers a constraint problem beside both the time dial setting (TDS) range, the plug setting multiplier (PSM) range of the relay, in which the horizontal axis represents the fault location and the vertical axis represents the tripping time. The problem is extremely complicated, both in terms of the constraints set and the objective function (OF) (Perez & Urdaneta, 1999).

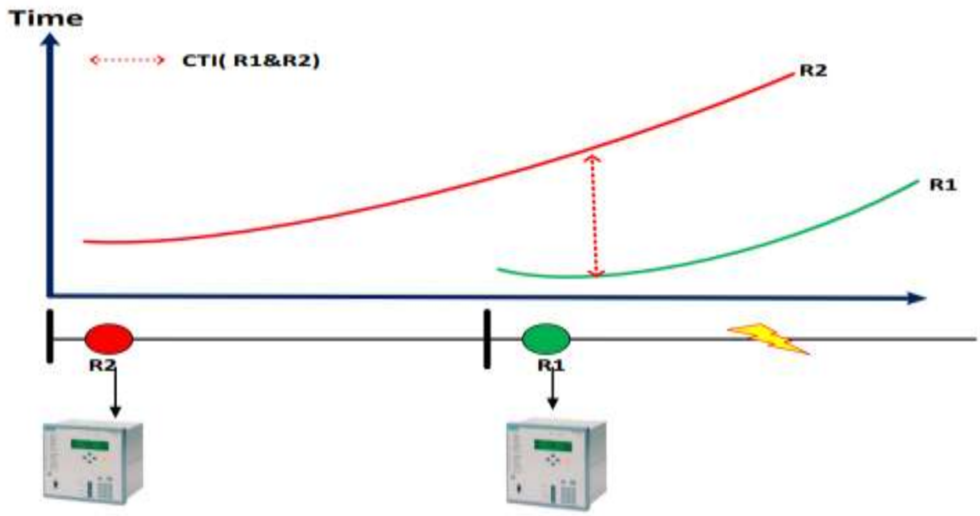


Figure 1.3: Coordination Constraint between Primary and Backup relay R1 and R2.

Conventional coordination between OCRs is often based on the assumption that network conditions and parameters such as resistance, current, and voltage remain constant during a failure (Meskin, Domijan, & Grinberg, 2015). Equation 1.1 explains the CTI between the OCRs for the primary relay and the backup relay for short circuits. The CTI is presented so that the coordination time between the backup relay, t_b, and the primary relay, t_p, is equal to or greater than the designated CTI (El-Naily, Saad, & Mohamed, 2020) (Rajput, Adelnia, & Pandya, 2018).

$$t_b - t_p \geq CTI \quad (1.1)$$

where the coordination interval time is (CTI), the tripping time of the backup relay is (t_b) and the tripping time of the primary relay is (t_p).

Variations in fault current cause an operation time between primary and backup relays that is less than the selected CTI, resulting in a miscoordination event. Calculations of the OCR's tripping time, t, using conventional methods are based on continuous fault currents and known fault currents, Isc, as depicted in Equations 1.2 and 1.3. The OCRs operating characteristics can be classified into define current, define time and inverse time, the last one is considered the most common kind of OCRs due to its feature (Paithankar & Bhide, 2022), (Juan M Gers & Holmes, 2004). OCRs utilize inverse time characteristics to ensure a more stable coordination with neighbouring protection devices. The inverse-time overcurrent element characteristics are adjusted based on the relevant standards of IEEE standard ("IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays," 1997), IEC standard (Relay-Part, 1989) and AREVA (Kucuksari & Karady, 2009), they are listed in Table 1.1. An inverse-time OCR characteristic can be mathematically stated by using Equations 1.2 and 1.3 defined by IEC and IEEE standards, respectively, as:

$$t = \left[\frac{\mathrm{A}}{\left(\frac{Isc}{Ip}\right)^{\mathrm{B}} - 1}\right] \mathrm{TMS} \quad (1.2)$$

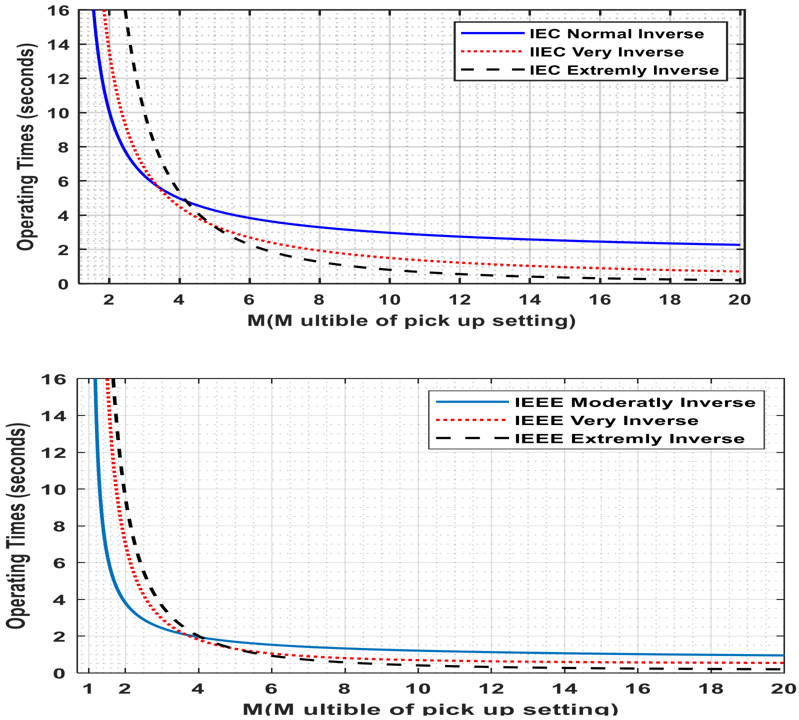
$$t = \left[\frac{\mathrm{A}}{\left(\frac{Isc}{Ip}\right)^{\mathrm{B}} - 1} + C\right] \mathrm{TMS} \quad (1.3)$$

where the OCR tripping time (t) in seconds (s) is for a known short-circuit current (Isc), for adjusting the time delay of the OCR, protection engineers need to set the time multiplier setting (TMS), (Ip) is the pickup current .(A), (B), and (C) are constants specifying the type of time curve characteristic used as illustrated below in Table 1.1.

Table 1.1: IEC, IEEE and AREVA Standardised Curves Characteristic Constants

Standard	Curve	A	B	C
IEC	NI	0.14	0.02	0
	VI	13.5	2	0
	EI	80	2	0
IEEE	NI	0.0515	0.02	0.114
	VI	19.61	2	0.491
	EI	28.2	2	0.1218
AREVA	STI	0.05	0.04	0
	LTI	120	1	0

For different fault currents, magnitudes graphical representations of the IEC standard characteristics are illustrated in Figure 1.4(a) (Relay-Part, 1989), while the IEEE standard characteristics give the visual depiction of the responses and can be seen in Figure 1.4 (b) ("IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays," 1997). However, adding DG to a network will change the nature of the fault current that travels through the primary and backup relays. Consequently, the standard protection method, as detailed in this section, will have difficulties coordinating the relays, new schemes must be implemented. In addition, The Normal inverse (NI), very inverse (VI), extremely inverse (EI), short time inverse (STI), and long time inverse (LTI).



(a)

(b)

Figure 1.4: (a) Characteristics of inverse time OCR by using the IEC 60255-3 Standard, (b) Characteristics of inverse time OCR by using the IEEE C37.112-1996 Standard.

1.2 The Impact of DGs on the Overcurrent Protection Schemes

Short-circuit faults occur in electrical networks, which can damage equipment and cause dangerous conditions for the utilities and consumers. In such cases, detecting and clearing these faults should be done as quickly as possible. Typically, the greatest magnitude of short-circuit current in the network is a three-phase fault under normal conditions. Although the highest level would be obtained by other fault types, for example, the magnitude of the current phase-to-ground faults near solid-ground generators is significantly higher than that of a three-phase one. The level of the fault current depends on the topology of the network, the number of service generators, and the grounding arrangements. Moreover, OCRs pick-up settings and the coordination between the OCRs should consider anything that can affect them.

In a power system with sources of several high capacities, the short current magnitude is not be changed by adding small DG units. However, the fault current level is affected by the integration of numerous small and medium-sized DG units or high-potential DG units. Thus, during fault calculations, these conditions must be taken into consideration. The DG unit's contribution to the fault current is dependent on the DG unit type, which can be described as inverter-based distributed generation (IDGs) such as wind turbines and photovoltaic systems or synchronous distributed generation (SDGs). However, the extent of each type's contribution and response to the fault current varies.

Generally, conventional OCR characteristics focus on load and fault currents in relation to trapping time (Nassif, Loi, Wheeler, & Bahramirad, 2022). Whereas they do not take into consideration the power network integrated with DGs, which affects load and fault current. The main impact of integrating DGs with the main grid is reduced short circuit currents that pass through several branches of DN, which leads to miscoordination and setting response issues between OCRs during the grid connected and islanding operation modes. Due to loss of protection coordination, there are several problems that are expected to occur, especially blindness of protection, sympathetic tripping. The points below and Figure 1.5 illustrate different main OCR protection challenges of penetration DG units in the power system (N. Hussain, Nasir, Vasquez, & Guerrero, 2020). The main protection challenges of OCRs in an existing network with DG units are presented in Figure 1.5 and summarised as follows:

- Blinding tripping is a condition in which an OCR is unable to detect a fault due to distorted current waveforms resulting from the presence of harmonic currents within the system. The incorporation of DG into the power grid has been identified as a potential cause of harmonic distortions due to the DG's inverter. Such distortions may prevent the OCR from identifying faults accurately, thereby increasing the likelihood of equipment damage and power outages. Thus, the phenomenon of blinding tripping can pose a significant challenge to the reliable operation of power systems, and measures to mitigate its effects must be pursued (Bak-Jensen et al., 2015).
- Sympathetic tripping, also known as false tripping, is a scenario in which an OCR mistakenly trips when there is no actual fault present or when the OCR cannot differentiate between normal operation and a fault of a DG system. This faulty tripping can result in unnecessary shutdowns of the DG, thereby lowering the system's overall

reliability. Consequently, false tripping is a critical issue that must be carefully addressed to ensure power systems' stable and secure operation (Beheshtaein, Cuzner, Savaghebi, & Guerrero, 2019).

- Loss of coordination refers to the potential disruption of the coordination and control of centralized power systems by DGs, which may result in voltage and frequency fluctuations and the loss of selectivity between OCRs. The incorporation of DGs can lead to issues in the coordination of protective devices, and a lack of coordination may result in incorrect or inadequate responses during faults, leading to equipment damage or power outages (Yazdanpanahi, Li, & Xu, 2012).
- Islanding detection is another critical concern associated with DG integration. DGs can continue to generate power even when disconnected from the main grid, resulting in an islanded power system. OCRs must be capable of detecting such islanding and trip the DG to prevent it from continuing to supply power, which can lead to safety concerns and equipment damage (Laaksonen, 2010).
- The integration of DGs, such as solar photovoltaics (PV) and wind turbines, can cause bidirectional power flow, leading to challenges for traditional OCRs that are designed to handle unidirectional power flow. The bidirectional power flow causes protection devices to respond differently to power system conditions, leading to over or under-reach, equipment damage, and OCR malfunctions. Hence, OCRs must be capable of accurately detecting bidirectional power flow to ensure the safe and stable operation of power systems (Teimourzadeh, Aminifar, Davarpanah, & Guerrero, 2016).
- DG systems can introduce a range of fault current levels and directions into the power grid due to their connection points and differing contributions. This variability in fault currents can create challenges in detecting and localising faults, leading to potential difficulties in maintaining the stability and security of the power system. Furthermore, during a fault, the direction of the fault current can change rapidly, which poses additional challenges for OCRs to respond quickly and accurately. Hence, effective measures must be employed to address these issues and ensure the reliable operation of the power system (Telukunta, Pradhan, Agrawal, Singh, & Srivani, 2017).

In this thesis, the proposed novel hybrid optimal OCRs coordination approach based on novel nonstandard time current characteristics (NSTCC) and another new non-standard characteristic approach (N-SCA) based on new water cycle moth flame optimization (HWCMFO) algorithm will work to minimise or avoiding the impact of the above challenges. The novel hybrid optimal

OCRs coordination approach aims to minimise total OCR tripping time while avoiding any less coordination, blinding tripping, or sympathetic tripping events. In addition, the proposed protection approach will be evaluated under different grid operation modes, such as islanding, and under different fault scenarios.

Figure 1.5: The Protection Challenges of OCRs with Existing DG Units (N. Hussain et al., 2020)

Various solutions have been proposed to tackle the challenges of OCRs in power systems with DGs. These include the following:

- Advanced protection schemes, such as adaptive protection, differential protection, and microprocessor-based protection, can enhance the accuracy and reliability of OCRs by quickly and accurately detecting and locating faults and reducing the likelihood of false trips (A. U. Khan, Hong, Dyśko, & Booth, 2019).
- Harmonic filtering techniques, including passive and active filters, can reduce the distortion caused by DGs on the power system, thereby improving the accuracy of current measurements and reducing the possibility of blinding (Kiliçkiran et al., 2018).
- Islanding detection algorithms can be incorporated into OCRs to detect when DGs are disconnected from the grid and trip them, preventing DGs from generating power and protecting the grid against potential power outages (Nsaif, Lipu, Ayob, Yusof, & Hussain, 2021).

- Fault current limiters (FCLs) can limit the amount of fault current during a fault event and allocate OCR coordination in DG power systems, protecting equipment, improving the grid's stability, and minimizing disturbances to the power supply. FCLs can also reduce the risk of cascading failures by preventing high fault currents from propagating through the system and causing additional faults (Elmitwally, Gouda, & Eladawy, 2015).
- Finally, OCR coordination optimization methods can optimize power output and flow while meeting constraints such as voltage and power balance. These methods have been shown to improve OCR reliability and ensure selectivity between OCRs in power systems with DGs. By adopting these solutions, power systems with DGs can maintain high reliability, stability, and security levels (Usama et al., 2021).

1.3 The Problem Statement: OCR Coordination

OCR coordination refers to the process of ensuring that overcurrent protection devices in an electrical power system are properly coordinated to operate in the correct sequence and at the appropriate time during a fault or overload condition. This thesis will outline the main challenges of integrating DGs to the DN in terms of power protection performance and present a solution to minimize the total tripping time of OCRs. Current research identifies the optimal OCRs coordination approach as a potentially major solution to enabling DN to become more efficient in terms of protection sensitivity and selectivity by minimising total tripping time. This thesis studies how the setting of OCRs on a DN with DGs can be optimally determined, in order to reduce the tripping time and achieve the maximum sensitivity and selectivity. Understanding the OCRs coordination problem at the DN is essential to reduce the relay tripping time. Therefore, this work introduces the coordination problem for OCRs in different grid operation modes in order to design the optimal protection scheme. The thesis will then investigate the performance of the proposed hybrid coordination scheme by demonstrating different simulation and testing for radial and mesh grids, including the connection and disconnection of DGs and islanding modes. In addition, this work investigates and studies different optimization algorithms for solving the OCRs coordination problem. The thesis aims to comprehensively understand the challenges and solutions for integrating DGs into the DN from a power protection perspective.

1.4 The Objectives

The principal aim is to introduce a study of various methods of the OCRs coordination in electrical power systems, utilizing nonstandard characteristics and an artificial intelligent method for determining the optimal settings for the OCRs being selective.

The main objectives of the current thesis are shown as below:

- Review the different methodologies utilized for obtaining optimal OCRs coordination with the presence and absence of DGs.
- Implement a hybrid algorithm as an optimization technique to solve the problem of OCRs coordination.
- Improve the performance of the optimization technique by applying it with nonstandard characteristics to maximise protection facets and compare it with the preceding investigation.
- Propose a workable protection solution and an economic scheme for the radial microgrid (MG) system.
- Design innovative nonstandard tripping protection scheme for meshed MG systems considering the islanding system operation.

1.5 Contributions of the Research

To back up the study problem statement offered in Section 1.3, Chapter 2 offers historical and up-to-date literature on OCR protection approaches for DNs equipped with DGs. Several research gaps have been identified through the present literature review, which has prompted the need for the study described in this thesis and highlighted the possible benefits of the work for the business sector and the scientific community. Several innovative features, briefly summarised below, help this thesis fill the void in the literature.

- For improving the performance of the protection system by integrating the DG units and with different fault levels for a range of fault scenarios in the MGs, the novel nonstandard time current characteristics (NSTCC) are created with consideration for the constraints of the existing model. In the OCR scheme, an optimum coordination approach is utilising NSTCC to reduce the total trip time compared to traditional standard characteristics and other nonstandard characteristics presented in the literature.
- An artificial intelligence hybrid algorithm based on water cycle moth flame optimisation (HWCMFO) has been developed inventively as an optimization technique

for OCRs coordination protection. Furthermore, this work highlights and investigates the issues built-in nowadays in industrial relays encountered, when using the optimization techniques without taking into account the tripping characteristics. This work examines and evaluates several optimization strategies to handle the OCRs coordination problem.

- This research investigates the proposed optimum coordination approach under various faulty conditions for two DN types: radial networks (IEEE 9-bus test system and IEC MG benchmark) and meshed networks (IEEE 9- and 30-bus test system). The comparison demonstrates the advantages of the suggested technique, particularly for the lowest fault in islanding mode. Furthermore, the proposed optimal coordination technique in this work only requires local acquisition of the current measurement; hence, no inter-OCR communication is necessary. Therefore, the suggested method reduces the need for a large communication infrastructure while still providing sufficient robustness to the OCR coordinating strategy.

1.6 Outline of the Thesis

This thesis is organised around two primary themes: first, developing a nonstandard protection scheme for OCRs. Second, the artificial intelligence hybrid and optimal algorithm to determine the optimal OCRs setting to achieve minimum trip time. This thesis's remaining chapters are organised as follows:

- **Chapter 2** presents a basic background, theories and comprehensive overview on the development of OCRs coordination methods to support the problem statement. The chapter delves into both conventional and nonstandard OCR schemes and methods, along with an analysis of optimization algorithms for solving OCRs coordination problem in DN with DGs and serves as an essential reference for researchers and practitioners in the field.
- **Chapter 3** provides a literature survey thorough examination of the current state of the art in OCR coordination methods from various research literature related to the current thesis that makes a research gap and what more have to be done.
- **Chapter 4** focuses on developing a nonstandard protection scheme known as a NSTCC with fewer constraints than optimal coordination schemes in the literature, because it employs a single flexible coordination method. The present chapter introduces different optimization techniques, including genetic algorithm (GA) and hybrid algorithm gravitational search algorithm-sequential quadratic Programming (GSA-SQP), as

common and standard optimization algorithms. This chapter examines and analyses the outcomes of the NSTCC and optimal optimization algorithms for OCR coordination in DN with contribution DGs in comparison to benchmarking methodologies.

- **Chapter 5** presents a new non-standard characteristic approach called (N-SCA) based on the HWCMFO technique, which is a novel algorithm designed to minimize the total tripping time of OCRs. This algorithm determines the optimal relay setting and considers the limitation of IEC characteristics when using it with the N-SCA at the power network with DGs and under different fault scenarios. The particle swarm optimization (PSO) algorithm is used as a standard optimization algorithm to compare it with the proposed HWCMFO technique. The chapter's exploration of state-of-the-art optimization techniques for OCR coordination provides important insights for researchers and practitioners seeking to optimize OCR coordination.

- **Chapter 6** an provide an overview of the research outcomes and a comprehensive conclusion in relation to the problem statement of the thesis. In addition, this chapter offers suggestions for prospective future studies based on the presented research.

Chapter 2: Background and Theories of the OCRs Coordination Methods

2.1 Introduction

Traditional overcurrent protection techniques are mainly applied for radial DNs. Still, the addition of DGs and the rise in the number of connections to DGs has complicated the idea of protection. For DGs, which have distinct modes such as grid-connected and islanded mode, as well as diverse topologies such as ring and mesh, the development of additional protection methods is necessary. Consideration of DG-induced features, such as bidirectional power flow, helps the development of alternate protection concepts for contemporary DNs. The previous chapter presented critical features of power system protection and discussed the effect of DGs on the protection of DNs, which plays a significant role in the design of the protection methods described in this thesis. In general, many OCRs protection schemes have been introduced in the literature until now. These protection schemes have been implemented to interconnect the DGs in grid-connected and islanded mode operation.

This chapter represents a comprehensive overview of most of the researchers' contributions in recent years. The purpose of proposing many coordination optimization frameworks is to obtain the best performance and determine optimal relay settings. This chapter focuses on discussing and analysing the following five key areas of research, as shown in Figure 2.1. At first, a review of the conventional, metaheuristic and hybrid optimization techniques is proposed. To improve the protection performance, the authors suggested applying new constraints for optimal coordination and the inclusion of additional constraints are introduced and investigated. Furthermore, many authors suggested modifying the OF to prevent OCRs miscoordination, which is demonstrated and examined in this literature. Another method is explained and addressed by several research efforts to reduce tripping time, which is a dual-setting protection scheme. Eventually, scholars have alternated the standard curves that are used for OCR's coordination with non-standard characteristics for enhancing protection power systems and avoiding miscoordination problems. It is important to emphasize that part of this chapter is from the published paper entitled "Overcurrent relays coordination optimization methods in distribution systems for microgrids: A review" which was presented at the 15th International Conference on Developments in Power System Protection (DPSP 2020). This paper, authored by S. Abeid and Y. Hu, is a comprehensive review of OCR coordination optimization methods in distribution systems for microgrids. It served as a foundation for the literature survey presented in chapter 2 of this PhD thesis. The insights and analysis provided in the paper are critical to understanding the current state-of-the-art of OCR coordination and form a significant contribution to this field. The main contribution in this paper is from S. Abeid as the first author including Conceptualization, methodologies investigation, writing—original draft preparation, writing—review and editing.

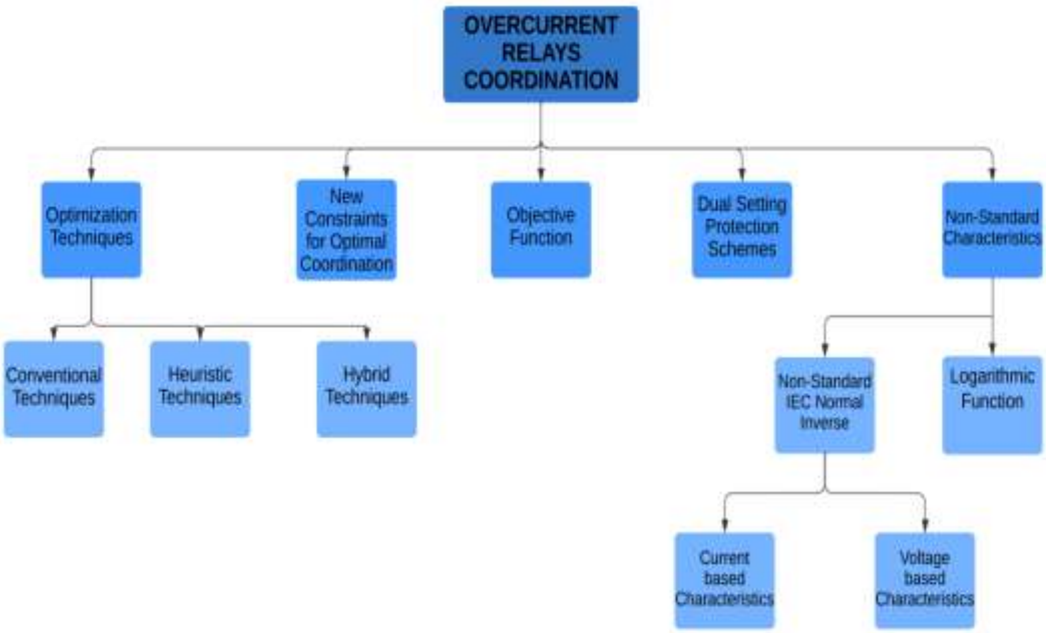


Figure 2.1: Overcurrent relays coordination methods

2.2 Optimization Techniques

An optimization problem is used to describe the OCR coordination issue that arises in a power network that is coupled to DGs. Normally, obtaining the relays optimum settings is considered the goal of optimization-based approaches. In this approach three main techniques which are: conventional techniques, heuristic techniques and hybrid techniques, it will be in detail as follows,

2.2.1 Conventional Methods

In conventional methods for OCRs coordination, the approaches could be classified into two main classes which include; trial and error, and topological analysis techniques (Barzegari, Bathaee, & Alizadeh) (Ezzeddine & Kaczmarek, 2011) (Tuitemwong & Premrudeepreechacharn, 2011) (Chaudhari, Upadhyay, & Ahemedabad, 2011) (Gholinezhad, Mazlumi, & Farhang, 2011), as shown in Figure 2.2. Firstly, the trial and error technique for selecting the optimal relay setting was introduced by (Thangaraj, Pant, & Deep, 2010) (Mansour, Mekhamer, & El-Kharbawe, 2007). However, this technique required a large number of iterations to attaining a suitable relay setting. To lower the iteration number needed for the process of coordination, they recommend a method for breaking each loop known as breakpoint and identify the first relays at each of these points. Identifying the breakpoints is an essential section for initiating the process of the coordination. Therefore, topological methods are applied for identifying the break points (Mansour et al., 2007) by comprising of graph and functional theory. Other topological analysis that are in linear graph theory are stretched to analysis every simple network loop in both directions minding the least set of breakpoints as well as the backup and basic relay pairs. This method provided the best solution for the relays settings but was not the global optimal setting. Implying that, the relay's TDS or TMS are increased. Besides, because of the system complexity, error and trial method and topological analysis are not optimal and are time consuming. Therefore, the curve fitting approaches, as graph theory, are applied in the identification of the finest function for representing data. The curve fitting techniques are applied in relay properties for mathematically analysing through polynomial (Smooolleck, 1979) ("Computer representation of overcurrent relay characteristics," 1989). The graph theoretical techniques also reported a

s the second category (Jenkins, Khincha, Shivakumar, & Dash, 1992). The system framework is applied for analysing the data on breakpoints minimum set, line directionality for directional relays, sequence for setting relay, and the entire basic or backup relays. The first work to outline the use of the optimization theory during directional overcurrent relay (DOCR) coordination was Conventional Method Trial & Error Topological Analysis Functional Graph Theory (A. J. Urdaneta, Nadira, & Perez Jimenez, 1988).

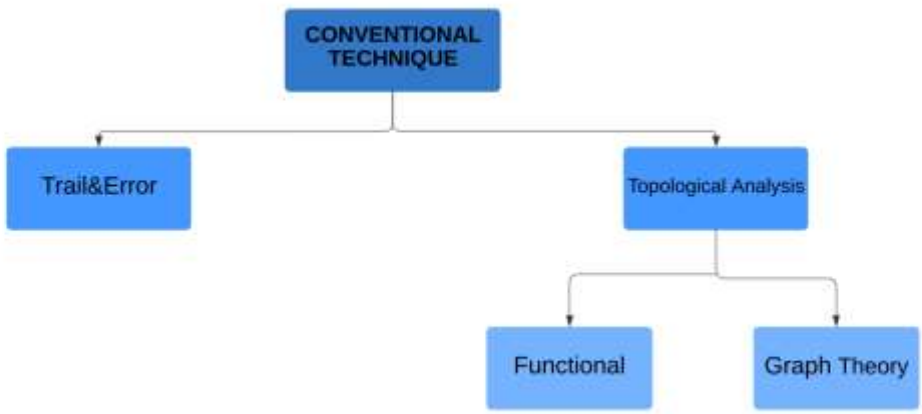


Figure 2.2: Approach of the conventional methods

In general, the functional optimization techniques overcome the rest of the conventional approaches limitations, in which OCRs have been placed in order prior to the coordination procedure (Mohammadi, Abyaneh, Rudsari, Fathi, & Rastegar, 2011). It has more attention among researchers due to its advantages, namely, that the need of finding the set of breakpoints is eliminated by using functional optimization techniques.

Several proposals have been achieved based on functional approach, where they considered the OCRs problem as a function problem. Whereby in (H. A. Abyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, & R. A. J. Khan, 2003), the calculation of TSM values was done through the Linear programming (LP) model, simplex technique for pickup current stated values. Some scholars applied the non-linear programming (NLP) in optimizing approach in order to find a solution for the coordination problem though the method was time consuming and complex. This is because the NLP method, depends on the TMS, Ip, and relay properties, optimized simultaneously. In (A. J. Urdaneta et al., 1988), (Noghabi, Sadeh, & Mashhadi, 2009) and (P. P. Bedekar & S. R. Bhide, 2011), they formulate the relay coordination problem as a mixed integer non-linear programming (MINLP) and solve it through General Algebraic Modelling System (GAMS) software. But, the application of binary variables to consider the discrete pickup currents, increases the coordination problem complexity (Birla, Maheshwari, & Gupta, 2005). Following the technique's complexity, the OCRs coordination is often conducted through LP approaches like the two-phase Simplex and Simplex, dual Simplex techniques (Rashtchi, Gholinezhad, & Farhang), (Razavi, Abyaneh, Al-Dabbagh, Mohammadi, & Torkaman, 2008), (M. Singh, Panigrahi, & Abhyankar), (Birla et al., 2005) and (Noghabi et al., 2009). The limitation of these methods is that they depend on first guess and could be trapped in the local minimum (Moravej, Jazaeri, & Gholamzadeh, 2012). The assumption in these techniques is that the pickup current, Ip settings is to be known and, in its TDS, or TMS, the OT for every relay is linear function.

(PRASHANT P Bedekar, Bhide, & Kale, 2009), recommends Big-M (penalty) technique for determining the overcurrent relays TMS whereby the assumption is that the PS (Ip) is fixed and known. This approach depends on the simplex algorithm applied to determine the optimal solution in LG questions. LP obtain a first primary feasible solution referred as (Initial Basic Feasible Solution) IBFS, artificial variables are introduced in the objective function. In addition, Bedekar et. al in (P. P. Bedekar, S. R. Bhide, & V. S. Kale), (P. P. Bedekar, S. R. Bhide, & V. S. Kale) and (Prashant P. Bedekar, Bhide, & Kale, 2010) suggested Simplex, two-phase Simplex, and dual Simplex techniques for solving the problem of DOCR in ring fed system of distribution. Following the recommended LP methods and Big-M (penalty) techniques, the next paper in (Prashant P. Bedekar, Sudhir R. Bhide, & Vijay S. Kale) made a comparison of the four techniques and it was indicated that in comparison to others, the dual-Simplex technique was most suitable. The authors stated that the calculations number for each iteration within dual-Simplex technique is lower than the other three techniques. Nevertheless, (Ezzeddine & Kaczmarek, 2011) explained that even when LP methods are simple and converge easily to optimal solutions, just the values of TSM could be optimized rather than pickup current, they have to select Ip through experience of load and fault data. Normally, this does not offer a global optimum solution or answer of the issue. Therefore, the application of these LP methods contains boundaries in relation of low constraint number (El-Fergany & Hasanien, 2019).

The traditional function algorithms we've talked about so far depend on where they start. They cannot merge into the global optimal except if a valid initial start is recognised (M. H. Hussain et al., 2013). Heuristic techniques that are gradient independent can overcome this disadvantage. Consequently, the heuristic techniques are improved to attain an optimal global solution in a reasonable amount of computational time at an optimal point in the research space and are most widely used for relay coordination.

2.2.2 Heuristic Technique

The protection approach for a DN with DGs needs to handle two significant obstacles: first, the stochastic behaviour of DGs, and second, the ability to run the DN with different operation modes. Due to the bidirectional and changeable short circuit currents (levels and direction), these difficulties raise the difficulty of creating an optimal protection coordination strategy (Najy, Zeineldin, & Woon, 2012). The protection system's need to ensure the stability and dependability of the network's intermittent DG units and loads. In order to discover the best OCR configuration in a MG, many methods have been proposed and applied in the literature. In previous section, when it comes to these challenges, conventional solutions have often concentrated on employing the well-known and practised OCR curves. However, conventional techniques perform poorly because they ignore the effect that DGs have on the network's power flow, fault characteristics, and protection system (Choudhary & Das, 2023b). Thus, it is clear that inventing and utilising a new optimization technique, such as a metaheuristic optimization algorithm, may be helpful in enhancing the performance of OCRs and resolving the coordination issues in a MG, especially due to its based on an artificial intelligence and nature inspired algorithms.

For example, genetic algorithm (GA) was successfully implemented for optimal coordination OCRs to reduce the OT of relays and reduce miscoordination problem (So, Li, Lai, & Fung). However, particle swarm optimization (PSO) was used in solving the formulation of the optimal relay settings by (H. Zeineldin, E. El-Saadany, & M. Salama, 2006) and was confirmed that PSO is more suitable for dealing with miscoordination issues for both discrete and continuous

PSM (Isc/Ip) and TSM instead of GA. In relation to the enhanced convergence properties, some GA improvements (H. Zeineldin et al., 2006) like progressive GA (Noghabi et al., 2009). They have adopted Evolutionary programming (So & Li, 2000) and various types of differential evaluation (DE) techniques like the adaptive DE (ADE) algorithm (Moirangthem, Krishnanand, Dash, & Ramaswami, 2013) and opposition-based chaotic DE algorithm in order to obtain the optimum setting of relays by the improvements of discrete values of decision variables (Chelliah, Thangaraj, Allamsetty, & Pant, 2014a). Although the above mentioned different heuristic optimization methods have obtained optimal coordination, they do not express the method of determining the OF weight factor''a key performance indicator for the optimization problem, which reveals the relative importance between the two objectives''. (Thangaraj et al., 2010) conducted an evaluation on the five varied versions of modified differential evolution (MDE) in order to comparatively judge their performance in offering a solution to the relay coordination problem. In these techniques, the local optimal influence the solution because of the constant scaling components. (H. H. Zeineldin, E. F. El-Saadany, & M. M. A. Salama, 2006) (Mansour et al., 2007) made an attempt to attain the OCRs coordination through the improved PSO methods. To acquire the OCRs optimum coordination in the ring-based power systems, (M. Singh, B. Panigrahi, & A. Abhyankar, 2013a) utilised the teaching learning-based optimization (TLBO) algorithm. Then, (Alipour, Teimourzadeh, & Seyedi, 2015) recommended an advanced group search optimization algorithm in the OCRs' coordination. In addition, in order to deal with the OCR coordination influenced by the dynamic alteration in the network topology and Ant colony optimization (ACO) have been applied in solving the coordination problem in OCRs (Shih, Salazar, & Enríquez, 2015). (Amraee, 2012) suggested a new seeker optimization method for the OCRs coordination. But, in most of the past techniques have a major deficiency is the convergence threat in the local optima. Firefly algorithm (FA) is selected to obtain an optimized OCR function (Benabid, Zellagui, Chaghi, & Boudour, 2014). In the optimization, the FA performance is related to a random value of Gaussian distribution that results to moderate trapping and convergence during the local optimising point. Thus, an advanced adaptive modified FA (AMFA) is suggested to determine the OCRs optimal coordination. AMFA amends the FA through the manner of investigation in the search of the OCRs' optimum coordination and increasing the speed in the convergence (Tjahjono et al., 2017). An ant lion optimiser (ALO) is applied to solve coordination problem as a constrained optimization problem. In the distribution system, the OF was targeting a minimum OT of OCRs (Hatata & Lafi, 2018). A new optimization technique called water cycle algorithm (WCA) is presented to deal with the problem of OCRs coordination. To define the best OCR setting, the adapted problem is mathematically formulated (El-Fergany & Hasanien, 2019). To solve the problem of directional DOCRs coordination, an enhanced version of grey wolf optimiser (EGWO) is proposed for improving the computation time and convergence characteristics of the traditional grey wolf optimiser (GWO) that by choosing a appropriate balance between exploring and exploiting phases (Kamel, Korashy, Youssef, & Jurado, 2020). New metaheuristic technique called surrogate assisted particle swarm optimization (SAPSO) is proposed in (Lalitha, Manoranjitham, Weslin, & Senthilselvi, 2021) for the DOCRs optimal coordination, multi-objective approach uses to solve coordination problems for both double configuration and grid-connected. The CTI was considered to be one of the objectives during the tripping time of all relays and investigated simultaneously, taking into account the constraints of the network and the autonomous mode. The protection scheme has been tested with the standard bus systems IEEE 6 and 30.

Sometimes, heuristic techniques can't find feasible solutions or the best global solution because there aren't any specific algorithms that can solve all the different parts of optimization tasks. The problems with the original candidate algorithm variant can be fixed by combining it with another algorithm to make it better. In this regard, optimal solutions can be yielded by improved or hybrid techniques better than the original ones (Noghabi et al., 2009).

2.2.3 Hybrid Techniques

In the search process, some heuristics perform better than others. This has to be examined more closely in the future in order to be able to produce hybrid metaheuristics that perform considerably better than their "pure" parents. In fact, we can find this phenomenon in many facets of life, not just in the world of algorithms. Mixing and hybridising is often better than purification (Blum & Roli, 2003). Moreover, most of hybrid structures have been adopted for improving the performance obtained in resolving the problem of OCR coordination. Within those techniques, non-dominated sorting GA-II and hybrid GA (Noghabi et al., 2009) (Bottura, Bernardes, Oleskovicz, & Asada, 2017), have been exercised to lower coordination times of backup/basic relay pairs and relay operating times. (P. P. Bedekar & S. R. Bhide, 2011) (Prashant P. Bedekar & Sudhir R. Bhide, 2011) made a contribution toward obtaining the global optimum values for PS and TMS through Hybrid (GA-NLP) technique and recommended continuous genetic Algorithm (CGA) in order to lower the function time of relays and eliminate the mal-operation of the relays. (Liu & Yang) proposed particle swarm optimization (NM-PSO) and a hybrid nelder-mead simplex search method. This technique is applied to enhance the efficacy of the PSO for fast feasibility, convergence, and computation speed. A hybrid gravitational search algorithm and sequential quadratic programming (GSA-SQP) has been introduced such one of the solutions of the OCRs coordination problem; it has been tested and evaluated on various test systems (Radosavljević & Jevtić, 2016). A hybrid particle swarm optimization and moth- flame optimization (PSOMFO) has been combined MFO for exploration phase and PSO for exploitation phase; the results seem to be effective compared to standard MFO and PSO algorithm (Bhesdadiya et al., 2017). Utilising the setting groups concept, an Adaptive Protection Scheme (APS) is proposed to rise the reliability of the system. For network topology changes, a hybrid LP and GA method is used to solve the problem. Thus, to classify the network topology changes scenarios into a limited number of setting groups and to use the LP algorithm to optimally coordinates the OCRs within the setting groups (Chabanloo, Safari, & Roshanagh, 2018). There is a new proposed algorithm is using hybrid whale optimization algorithm and grey wolf optimiser (HWGO), which is applied for enhancing the reliability and performance of the conventional whale optimization algorithm (WOA), the result have shown the ability of HWGO algorithm to overcome the weakness of the traditional WOA in terms of overcurrent coordination problem (Korashy, Kamel, Jurado, & Youssef, 2019).

For obtaining a clear view for the optimization techniques, different methods that have been proposed by authors or researchers with specific references for OCRs coordination are summarised in the Table 2.1.

Table 2.1: Overcurrent Relay Coordination Optimization Methods Publications

Algorithm	Abbreviation	Authors	Year	System Buses
Non-linear Programming	NLP	(Alberto J Urdaneta, Nadira, & Jimenez, 1988)	1988	3, 6, 30
Linear Programming	LP	(A. J. Urdaneta, Restrepo, Marquez, & Sanchez, 1996)	1996	18
Genetic Algorithm	GA	(So et al.)	1997	Case study
Computer Aided		(Perez & Urdaneta, 1999)	1999	Case study
Evaluation Programming	EP	(So & Li, 2000)	2000	Case study
Linear Programming Interior Point	LPIP	(A. J. Urdaneta, Pérez, Gómez, Feijoo, & González, 2001)	2001	9, 108
Linear Programming Technique	LP	(Abdelaziz, Talaat, Nosseir, & Hajjar, 2002)	2002	30

Linear and Non-Linear Programming	LP-NLP	(H. A. Abyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, & R. J. Khan, 2003)	2003	8, England Norweb Network
Non-linear Programming	NLP	(Zeienldin, El-Saadany, & Salama)	2004	3
Mixed Integer Programming	MIP	(H. Zeineldin, E. F. El-Saadany, & M. A. Salama)	2005	8
Particle Swarm Optimization. Modified particle swarm optimization. Sequential Quadratic Programming method. Random Search Technique	PSO MPSO SQP RST	(H. H. Zeineldin, E. F. El-Saadany, & M. M. A. Salama) (H. H. Zeineldin et al., 2006) (Birla, Maheshwari, & Gupta, 2006) (Deep, Birla, Maheshwari, Gupta, & Takur, 2006)	2006	Case study 8,14 6, 30 3, 4
Modified Particle Swarm Optimiser	MPSO	(Mansour et al., 2007)	2007	3,6,8
Genetic Algorithm	GA	(Razavi et al., 2008)	2008	6, 8
hybrid GA	HGA	(Noghabi et al., 2009)	2009	
Simplex Method Modified Differential Evolution Algorithms	SM MDE	(Prashant P. Bedekar et al., 2010) (Thangaraj et al., 2010)	2010	Case study 3, 4, 6
Hybrid Genetic Algorithm Non-Linear Programming Approach. Continuous Genetic Algorithm. Partial Differentiation Approach	GA-NLP CGA PDA	(P. P. Bedekar & S. R. Bhide, 2011) (Prashant P. Bedekar & Sudhir R. Bhide, 2011) (Chen, Lee, & Chang, 2011)	2011	15, 3 Case study 8
Seeker Algorithm	SA	(Amraee, 2012)	2012	3, 8, 15
Numerical Teaching Learning-Based Optimization. Artificial Bee Colony algorithm.	Numerical TLBO ABC	(Lu & Chung, 2013) (Manohar Singh et al., 2013a) (M. Singh, B. K. Panigrahi, & A. R. Abhyankar, 2013b)	2013 continue 2013	6, 7 3, 4, 6 9

Multiple Embedded Crossover PSO.	MECPO	(Farzinfar, Jazaeri, & Razavi, 2014)	2014	8, 14
Opposition Based Chaotic Differential Evolution Algorithm	OCDE	(Chelliah, Thangaraj, Allamsetty, & Pant, 2014b)		3, 4, 6, 14
Gravitational Search Algorithm.	GSA	(Tripathi & Krishan, 2014)		4
Biogeography-Based Optimization.	BBO	(Albasri et al., 2015)	2015	3, 4, 8, 9
Quadratically Constrained Quadratic Programming	QCQP	(Papaspiliotopoulos, Korres, & Maratos, 2015)		3, 8, 30
Local Fit Method	LFit	(Negrao & Vieira, 2016)	2016	8
Modified Adaptive Teaching Learning Based Optimization Algorithm	MATLBO	(Kalage & Ghawghawe, 2016)		6, 8, 9, 15
Real Coded Genetic Algorithm	RCGA	(Thakur & Kumar, 2016)		3, 4, 6, 14
Hyper-Spherical Search Algorithm	HSS	(Ahmadi, Karami, Sanjari, Tarimoradi, & Gharehpetian, 2016)		8
Piece-Wise Linear	PWL	(Ojaghi & Ghahremani, 2016)		Case study
Hybrid Gravitational Search Algorithm and Sequential Quadratic Programming	HGSA-SQP	(Radosavljević & Jevtić, 2016)		3, 9, 30
Gravitational Search Algorithm	GSA	(Srivastava, Tripathi, Krishan, & Parida, 2017)	2017	4
Differential Evolution Algorithm	DE	(Shih, Conde, Leonowicz, & Martirano, 2017)		5
Hybrid Genetic Algorithm	HGA	(Bottura et al., 2017)		Case study
Enhanced Differential Evolution Algorithm	EDE	(Shih, Conde Enríquez, Hsiao, & Torres Treviño, 2017)		14, 57
#Adaptive Modified Firefly Algorithm	AMFA	(Tjahjono et al., 2017)		Case study
A Hybrid Particle Swarm Optimization and Moth-Flame Optimization	PSO-MFO	(Bhesdadiya et al., 2017)		Four benchmark test functions
Mixed integer linear programming	MILP	(Damchi, Dolatabadi, Mashhadi, & Sadeh, 2018)		3, 8, 14, 30

A Hybrid Genetic Algorithm and Linear Programming Method	GA-LP	(Chabanloo, Safari, et al., 2018)	2018	11, 30
Invasive Weed Optimization	IWO	(Castillo, Conde, & Shih, 2018)		9,14,30,57,118
Continuous Particle Swarm Optimization	CPSO	(A. Wadood, Kim, Khurshiad, Farkoush, & Rhee, 2018)		Case study
Multi-Objective Particle Swarm Optimization) and Fuzzy Decision-Making	MOPSO/FDM	(Baghaee, Mirsalim, Gharehpetian, & Talebi, 2018)		8, 30
An Ant Lion Optimiser	ALO	(Hatata & Lafi, 2018)		Egyptian network11,33
Evaporation Rate Water Cycle Algorithm	ER-WCA	(Korashy, Kamel, Youssef, & Jurado, 2018)		15 Meshed
Hybrid Whale Optimization Algorithm and Grey Wolf Optimizer	HWGO	(Korashy, Kamel, Jurado, et al., 2019)	2019	9, 30
Water Cycle Algorithm	WCA	(El-Fergany & Hasanien, 2019)		15, 30
Modified Water Cycle Algorithm	MWCA	(Korashy, Kamel, Youssef, & Jurado, 2019)		9, 8, 15, 30
Improved firefly algorithm.	IFA	(Khurshaid et al., 2019)		6, 9, 30
Convexified Linear Program	CLP	(Stp, Verma, & Swarup, 2019)		3, 9, 15, 30
Enhanced Grey Wolf Optimizer	EWGO	(Kamel et al., 2020)	2020	8,9,15,30
Sine Cosine Algorithm.	SCA	(Sarwagya, Nayak, & Ranjan, 2020)		3, 15, 30
Imperialistic Competition Algorithm	ICA	(Alaee & Amraee, 2020)		3, 8, 15
Human Behaviour-Based Optimal	HBBO	(Behkam, Vahidi, Zolfaghari, Naderi, & Gharehpetian, 2020)		6
Hybrid Linear Programming and Variable Neighbourhood Search	VNS-LP	(Damchi & Dolatabadi, 2020)		6, 14, 15, 30
Firefly Algorithm	FA	(Rahmatullah, Diah, Dewantara, & Achmad, 2020)		Single Line Diagram
Enhanced L-SHADE algorithm	eL-SHADE	(K. H. Khan, Thapa, & Karki, 2020)		30, 57

Improved Moth-flame Optimization	IMFO	(Korashy, Kamel, Alquthami, & Jurado, 2020)	continue 2020	8, 9, 15
Simulated Annealing–Linear Programming	SA-LP	(Kida, Rivas, & Gallego, 2020)		3, 6, 8, 15, 30
Support Vector Machine.	SVM	(Vijayachandran & Shenoy, 2020)		Case study, 4
Harris Hawks Optimizer and Jaya.	HHO and Jaya	(Yu, Kim, & Rhee, 2020)		3,4,8,9
New Iterative Linear Program	NILP	(Srinivas & Shanti Swarup, 2021)	2021	3, 8, 30
Variable Neighbourhood Search	VNS	(Bouchekara et al., 2021)		8, 9, 15
Marine Predator Algorithm	MPA	(Abdul Wadood, Khan, Khan, Ali, & Rehman, 2021)		9
Modified Evaporation Rate Water Cycle Algorithm	MERWC	(Korashy, Kamel, Houssein, Jurado, & Hashim, 2021)		39 Meshed
Modified Harris Hawk Optimization	MHHO	(Irfan, Oh, & Rhee, 2021)		8, 15
Development of the dynamic Fitness-Distance Balance and an Improve Manta Ray Foraging Optimization Algorithm	dFDB and dFDB – MRFO	(Kahraman et al., 2021)		3, 4, 8, 9, 30
Crow Search Algorithm	CSA	(Sarkar & Kudkelwar, 2021)		IEC MG benchmark for both
Hybrid Harmony Search and Simulated Annealing	HS-SA	(Saldarriaga-Zuluaga, López-Lezama, & Muñoz-Galeano, 2021a)		
Opposition Based Learning Fractional Order Class Topper Optimization algorithm.	(OBL-FOCTO)	(Choudhary & Das, 2021)		3, 4, 30
Surrogate Assisted Particle Swarm Optimization.	SAPSO	(Lalitha et al., 2021)		6, 30
Improved Seagull Optimization Algorithm	ISOA	(Abdelhamid, Houssein, Mahdy, Selim, & Kamel, 2022)	2022	8, 14
Firefly Algorithm and Linear Programming	FA-LP	(Habib et al., 2022; Ramli, Mokhlis, Wong, Muhammad, & Mansor, 2022)		8, 15, 30
Hybridization Particle Swarm Optimization	HPSO			9, 14
				3, 9, 30
Adaptive	AFDBA	(Sampaio et al., 2022)		

Fuzzy Directional Bat Algorithm			continue 2022	
Hybrid Opposition-Based Learning-Aggrandized Class Topper Optimization	OBL-ACTO	(Choudhary & Das, 2023a)	2023	30
Multi-objective Artificial Cooperative Search Algorithm	MOACS	(Pavankumar, Debnath, & Paul, 2023)		Low voltage MG test system
Merging Particle Swarm Optimization and Crow Search Algorithm	PSO-CSA	(Shad, Gandomkar, & Nikoukar, 2023)		30 ring, 69 radial
Salp Swarm Algorithm	SSA	(Selim, Kamel, Mohamed, & Yu, 2023)		33, 69, 94 Portuguese

Table 2.1 above illustrates different types of optimization techniques and mentions the majority of mathematical, heuristic, and hybrid techniques over the last four decades. The inspiration behind this study is to investigate an effective WCA and MFO hybridization that can profit from both algorithms' benefits in HWCMFO, which is inspired by (Khalilpourazari & Khalilpourazary, 2019). The HWCMFO can provide substantially stable and effective approaches to complicated optimization problems. Such a problem is the MG protection coordination problem. The present thesis has introduced a HWCMFO algorithm as one of the solutions for solving these problems. The PSO algorithm is used for comparative purposes. In addition, GA and GSA-SQP algorithms are used in this thesis and feature an innovative nonstandard tripping protection scheme due to their radial and meshed MG systems, which will be presented in detail in the next chapters.

2.3 New Constraints and Inclusion of Additional Constraints

Besides the typical coordination constraints, proposing additional constraints can be a solution for avoiding sympathy trips and ensuring selectivity between the OCRs. Most authors aim to include new constraints for optimal OCRs coordination. In (Purwar, Vishwakarma, & Singh, 2017) the author includes a novel constraint with respect to the operational status of variables in the distributed system within DG. In (Damchi et al., 2018) (Manohar Singh, Telukunta, & Srivani, 2018) they suggested other constraints taking into consideration transient stability (Aghdam, Karegar, & Zeineldin, 2017), fault current direction (Sharaf, Zeineldin, Ibrahim, & El Zahab, 2014), and OCR coordination with distance protection scheme. Additionally, in (Damchi et al., 2018) the author introduced a constraint considers the parameters of entire OCR characteristics (Salazar, Enríquez, & Schaeffer, 2015) and constraint in consideration of single outage contingency [N−1] (Amin Yazdaninejadi, Golshannavaz, Nazarpour, Teimourzadeh, & Aminifar, 2018). A constraint deliberates fault ride by the necessities for transmission level interconnected wind parks in (Khaled A Saleh, El Moursi, & Zeineldin, 2015), and varying network topologies in (Noghabi et al., 2009) had been recommended. All the types of short-circuit contributions in optimization of OCR coordination problem taken into consideration in (Ehrenberger & Švec, 2017). A new constraint reduction for the distribution system with high penetration of the DGs has been proposed, which based on optimal relay coordination method. The independent settings for different feeder zones have been determined by the proposed method, where if mode gets changed there is no need of re-optimization for new TDS (Purwar et al., 2019).

For different MG topologies, a novel constraint represented the plug setting multiplier operating region in industrial OCR curves had been investigated and verified (Saad, El-Naily, & Mohamed, 2019). In (Sati & Azzouz, 2021), a special protection scheme just for islanded MGs has been proposed. The proposed scheme uses an FCL for protection coordination purposes. The proposed is applied in two stages. Calculation of the relays short-circuit currents in the first stage. Afterwards, formulation the constraints on the primary and backup DOCRs OTs for the islanded mode and every potential mode following an N-1 contingency. Finally, in stage 2, the optimal protection coordination is subedited as a constrained problem and resolved to acquire the optimal settings of DOCRs. A study has been developed a sensitive overcurrent protection scheme based on a piece-wise linear characteristic (PWLC) in meshed networks. Series connection of the straight-line segments determine the overall time current characteristics of the relays in different protection zones. Authors used parameters A and B in IEC standard equation as variable coefficient constraints, which their values between IEC NI and IEC VI. The novel proposed method is improved the sensitivity of the relays and papered its robustness in terms of selectivity and reliability (Azari, Mazlumi, & Ojaghi, 2022).

It seems to be adding new constraints, which played a key role in solving the OCRs coordination problem. Although the proposed methods mentioned above have contributed to reducing the total trip time compared to traditional standard characteristics, they have some disadvantages, such as increasing the computational costs and affecting the computational speed, particularly, in (Azari et al., 2022), the coefficient variables number is two that raise the computing issues. In the present thesis, the proposed approach uses one variable coordination scheme, which is a new constraint in the OCRs coordination solution. Thus, it can reduce the constraints in the computing process compared to optimum coordination in literature. Consequently, it achieves the optimal solution with lower computational costs.

2.4 *Modification the Objective Function*

One of the suggestions made by many authors to contribute to preventing the miscoordinations is modifying the OF. In (Razavi et al., 2008), authors introduced a special OF based on the optimization technique GA by introducing new parameters and adding new terms to OF, which proved its ability for solving the problem of discontinuous and continuous TMS's and ensuring the selectivity between relays. The OF in (Razavi et al., 2008) has been developed, and the new OF involves six pairs of the primary and backup currents and it removes the redundant term. Then, this OF is more efficient and favourable than the previous one (Mohammadi, Abyaneh, Razavi, Al-Dabbagh, & Sadeghi, 2010). A new OF is proposed for satisfying coordination constraints if they are not satisfied, among constraints with different weighting. It has been applied in multiloop networks, and the results are compared to previous methods that have shown the superiority of this approach (Mohammadi et al., 2011). Multiple modifications in the OF for DOCRs for meshed networks have been suggested by Alam et al (Alam, Das, & Pant, 2016); it minimized the OT for main and backup relays simultaneously. There is a comparison among the performance of several OFs has been made and evaluated on 30-bus system (IEEE standard) (Shah, Khristi, Rajput, & Pandya, 2017).

In (Amin Yazdaninejadi, Naderi, Gharehpetian, & Talavat, 2018), a novel OF is proposed to direct the settings of the OCRs towards optimal solutions suitably. The proposed approach showed a significant reduction in the OT of relays and avoided miscoordinations among them. For solving DOCRs coordination problem, another comparison has been presented in (Afifi, Sharaf, Sayed, & Ibrahim, 2019), which a single objective function is compared to multi-objective optimization approach to guarantee diminishing coordination breaches. The results of the proposed approach proved that the multi-objective function reduces the tripping time better than the single-objective function and is more reliable in terms of ensuring the coordination between OCRs. A novel OF is proposed for avoiding the sympathetic tripping problem in the MG in (El-Naily et al., 2020), the proposed scheme combined the phase and earth OCRs functions to obtain the optimal OCRs setting and enhance the selectivity between them in the MG. In radial distribution grid, optimization of multiple objective functions is used for the location and size of alternative energy and energy storages with digital OCRs and digital dual settings OCR. The proposed approach introduced two stages, firstly, optimizing the optimal size and location of the renewable energy sources (RESs) to decrease the raising and reducing of the voltage cost, decrease the losses cost and decrease the installation cost of the RESs and energy storages by using the weighted objective function. Secondly, ensuring the coordination between the OCRs and reducing the tripping time by adding two parameters to the IEC NI current characteristics (Rezaei, Gandomkar, & Nikoukar, 2022).

2.5 Dual Setting Protection Scheme

In contrast to most OCRs, a single OCR unit set to dual mode can perform both the main and backup functions. Therefore, the programming for every OCR dual setting is in two directions that is, reverse/backup and forward/primary, denoted by “fw/p” and “rv/b”, accordingly. Every direction function independently; thus, some of the interconnected coordination constraints are stress-free. These properties lead to an enhanced performance in decreasing the total operation time of the relays. However, research focus is devoted to the conventional DOCRs, very few studies have been conducted on dual-setting DOCRs. In the initial trial in (Dewadasa, Ghosh, & Ledwich), dual-setting DOCRs application was suggested for the protection of the radial distribution networks. It is noteworthy that regardless of employing DOCRs to tackle the bi-directional power flow faults in DG-mixed networks, the working time is still prolonged. Through increasing the penetration of DG, the coordination problem complexity deepens that leads to increased working times for relays. Consequently, it is expected to use dual-setting relays which have the ability to reduce the protection operation time and eliminate these challenges.

In a more recent attempt, the use of dual-setting OCRs was contemplated for the protection of DNs of several source meshed (Zeineldin, Sharaf, Ibrahim, & Abou El-Zahab, 2015). In (Sharaf, Zeineldin, & El-Saadany, 2018) they deployed the dual-setting OCRs for safeguarding a micro-grid with a capacity to function in both islanded modes and grid-connected. For all of the preceding researches, they recorded a significant decrease in the entire working time of relays. Though, they completely replaced the conventional relays with the dual-setting OCRs without considering the new scheme’s economic burden. Expectedly, dual-setting OCRs implementation sensibly lowers the working time in the initial stage of the replacement levels. But the decrease in the working time accumulates with increase in the penetration of dual-setting OCRs. The past research ignored such a crucial aspect because the entire relays were expected to be dual-setting OCRs. This occurs when; a maximum relay number together with the conventional ones can provide a rapid protection operation in a cost-effective way (Arab, Khodaei, Han, & Khator, 2015). There is a model of multi-objective optimization proposed which goals at minimising the relay total operating time through replacement level of traditional OCRs with an optimal number of dual-setting OCRs (Amin Yazdaninejadi, Golshannavaz, Nazarpour, Teimourzadeh, & Aminifar, 2019).

In meshed MG with presence of DGs, Thararak and Jirapong in (Thararak & Jirapong, 2020) proposed a quaternary protection approach with dual-DOCRs. An EP optimization technique is used, and a centralized protection control system based on the concept of smart grids is applied with the proposed protection approach to improve the dual-DOCRs adaptability. The outcome of this study is obtaining the optimal relays settings, ensuring the coordination between them and minimizing the relays OT. The performance of this method improved the sensitivity, selectivity and speed of MG protection systems. A new proposed has been deployed dual setting DOCRs and time-current- voltage characteristics simultaneously. It is introduced to meet the concern of protection coordination index in meshed DNs with interconnected DGs. User-define time-current-voltage characteristics can develop the proposed approach. This protection scheme can be implemented in numerical relays, where the study is conveyed in the protection logic form and respective logic blocks description. Findings proved a considerable advancement in the protection coordination index (Dadfar & Gandomkar, 2021).

A novel protection coordination scheme is introduced in (Tiwari, Singh, & Choudhary, 2022). It can be applicable in main MG operation modes namely grid-connected and islanded modes. The proposed approach is presented for dual setting-DOCRs utilizing a mix of different standard relay characteristics. Besides the parameters of TMS and PS for classic DOCR, dual setting -DOCRs are increased with a third parameter of relay characteristics identifier. According to the IEC-60255 standard, optimal relay characteristics can be selected by the third parameter from the standard relay characteristics. Even though, the scholars above found the dual settings protection scheme appropriate for radial and largely meshed DNs, the backup mal-operation drawback exists. Adding to this, the dual-settings method is such a complex procedure that it is unsuitable for industrial relays.

2.6 Non-Standard and User-Defined Characteristics:

It can be evident that due to the integration of DG units or MGs operation, the conventional characteristics are limited to face the OCRs coordination problem, specifically, during the interconnection of the MGs with IDGs during the islanded mode, the protective relays are desensitised due to the limitation of the fault current (Usama et al., 2021). Accordingly, unwanted relay tripping could occur, further undermining the reliability and selectivity of the coordination of OCRs. Consequently, a remarkable effort has been made to innovate non-standard characteristics (N-SCs) to treat the abovementioned issues. This part focuses mainly on providing details on the research that targets the construction of N-SCs so as to attain protection coordination in the power systems. These unconventional techniques are classified according to whether they contain electrical magnitudes.

2.6.1 Non-standard characteristics: IEC normal inverse including electrical magnitudes:
Previously, the relays which were applied to detect and clear a problem based only on the liability current value. Nevertheless, currently, the voltage value can be applied to establish the liability section of the power system because of the fact that OCRs is generally more accessible and capable of determining both voltage and current values by the fact that, they are linked to current via voltage transformers. According to the past study, these OCRs features offer a chance for the use of N-SCs that are created not just through considering the current as well as the voltage value (Dewadasa, Ghosh, Ledwich, & Wishart, 2011)-(Khaled A. Saleh, Zeineldin, Al-Hinai, & El-Saadany, 2015)-(Bayati, Dadkhah, Sadeghi, Vahidi, & Milani). Some studies have recommended the need to exploit the voltage measurements through integrating a voltage parameter to the standard characteristics (SCs) so that they can alleviate the impacts resulting from, MG, DG links etc., whilst others proposed application of the admittance depending on the properties offered that they preserve the inverse time properties. This section, the research compared attaining of relay coordination with respect to the different integrations of determined voltage and current values is analysed.

2.6.1.1 Current based characteristics (CBC)
There is still a possibility to produce N-SCs by merely depending on the current measurement, though SCs readily utilizes the current. Research applied current in varied approaches obtained from the SCs reviewed in this subsection. Industrial power systems comprise of very rich environment with respect to the protective devices. Many protective devices types like the fuses, digital relays, and electromechanical relays are observed in a similar industrial power system. Though, in this highly diverse environment, coordinating various forms of protective devices like the relay-fuse is a complex task when utilising standard techniques. They proposed application of N-SC, to tackle very complex coordination issues within the industrial power system (Arreola Soria, Conde Enríquez, & Trujillo Guajardo, 2014). In this property, the assumption is that a value shifts dynamically with respect to the measured current value rather than being constant. In (Arreola Soria et al., 2014) the characteristic equations are provided in Equations 2.1 and 2.2. Nevertheless, it is essential to ensure that A (Isc) function is determined with respect to the specific protection problem.

$$\mathrm{A}(Isc) = \mathrm{A} \times e\ -Isc/C \qquad (2.1)$$

$$t = \left[\frac{A(Isc)}{\left(\frac{Isc}{Ip}\right)^B - 1}\right] \times TMS \qquad (2.2)$$

where t is the tripping time (in seconds) of relay due to a fault type occurrence at location. A(Isc) is a variable function that dependents on the current. A, B and C are constant coefficients, they set as shown in Table 1.1. Isc is a short circuit current measured at the secondary winding of the current transformer of relay while Ip the pickup current is the minimum value of current above which the relay starts to operate and TMS is the time multiplier setting.

The goal was to establish functions, A(Isc), capable of modifying the relay's dynamic behaviour and either speeding up or slowing down the operation time based on the particular application. The suitability of the function A(Isc) might vary depending on the specific case study, though the flexibility of the relay model leads to improved configurations.

Other researches obtaining N-SCs depending on the determined current are presented in (Enríquez, Vázquez-Martínez, & Altuve-Ferrer, 2003) (Conde & Vázquez, 2007), that integrated the non-standard approaches and adaptive relay concept. They took the pickup current as a load current presented curve fitting approach depending on a polynomial equation, and it was used in a software that was specifically established for applications of relay coordination. However, the structure provided as an output equation through the equation was very complex and did not require setting automatic and parameters coordination; hence it was a superior property for this approach. Function in these investigations (Ip (IL)). Though, rather than applying an explicit equation, in ("Computer representation of overcurrent relay characteristics," 1989) they presented curve fitting approach depending on a polynomial equation, and it was used in a software that was specifically established for applications of relay coordination. However, the structure provided as an output equation through the equation was very complex and did not require setting automatic and parameters coordination; hence it was a superior property for this approach.

2.6.1.2 Voltage based characteristics (VBC)

The key underlying concept in using the voltage value which is observes through the relay is to offer reliable relay coordination in DG high penetration. Because the DG leads to the fault current, the different fault current indirectly influences the bus voltages in the system. (Khaled A. Saleh et al., 2015) was among the earliest researches which utilised the determined voltage value. (Zhang, Crossley, & Li, 2017) introduced the voltage value into the IEC standard property equation as a multiplier that lowered the relay t in every potential fault condition. Additionally, it was assumed that when the determined voltage value is zero the relay t uses the least value, which implies that a fault takes place at the relay's contact point. It must be noted that each unit value of the determined voltage (Vf) in Equation 2.3 is applied in this equation whereas in adjusting the effect of the voltage they make use of new constant k. Also noteworthy is the fact that they did not present any specific method of formulating the constant k in (Khaled A. Saleh et al., 2015) and thus, there still needs to be addressed in future study. Furthermore, in (Khaled A. Saleh et al., 2015) they suggest the impact of voltage on the N-SC.

$$\mathrm{t} = \left(\frac{1}{e^{(1-Vf)}}\right)^{k} \left[\frac{A}{\left(\frac{Isc}{Ip}\right)^{B}-1}\right] \times TMS \tag{2.3}$$

where *t* is the operation time, Vf is the per-unit equivalent of the phase fault voltage magnitude measured at relay for a fault type at location, while *K* is a constant parameter, Isc is the short circuit current, Ip is the pickup current, TMS is the time multiple setting of relays. And the constants *A* and *B* are set to 0.14 and 0.02, respectively.

Another important characteristic in this research is that it comprised of an instance of the utilisation of a non-standard technique on the protection needs at the level of transmission, centrally to most studies which focused purely on the system of distribution. They also examined Equation 2.3 under the dynamic network topologies after the outages in the power system in (Bayati et al.).

In (Jamali & Borhani-Bahabadi, 2017b) they adhered to leveraging the advantages of the SC while creating new properties, whereby the voltage parameter was applied in enhancing the coordination of the fuse-relay in the DG presence. In Equation 2.4 they provide the properties of the equation formed in (Jamali & Borhani-Bahabadi, 2017b). In the same manner Equation 2.3 (Khaled A. Saleh et al., 2015) the suggested the property equation was also incorporated per-unit voltage value (Vf) and a constant k. The relation between the N-SC characteristic and voltage change is visualised.

$$\mathrm{t} = \left(\frac{Vf}{e^{k-Vf}}\right) \left[\frac{A}{\left(\frac{Isc}{Ip}\right)^{B}-1}\right] \times TMS \tag{2.4}$$

where *t* is the operation time, Vf is the per-unit of the phase fault voltage magnitude, Isc is the short circuit current, Ip is the pickup current, TMS is the time multiple setting of relays and *A*, *B* and *k* are constant parameters.

An identical technique in relation to applying magnitudes of voltage is indicated in (Jamali & Borhani-Bahabadi, 2017a), which generated a new view through applying logarithmic function in the denominator. A person could mind the characteristic presented in Equation 2.5 in (Jamali & Borhani-Bahabadi, 2017a),as an integrated approach because its inclusion of both an electrical magnitudes and “unconventional” mathematical expression, as provided in Equation 2.5. It can be observed that if the voltage determined through the relay is zero, the relay’s tripping time based merely on the constant D.

$$t = [\frac{((\mathrm{Vf}))^{k}}{e^{Vf}} \left[\frac{A}{(\ln (Vn\frac{Isc}{Vf}))^{B} - (\ln (Vn\frac{Iset}{Vset}))^{B}} + C\right] + D] \times TMS \tag{2.5}$$

where t is the operating time, Vf is the phase fault voltage magnitude and Vn is the nominal phase voltage. Isc is the fault current. $Vset$ is the voltage settings, $Iset$ is the current settings. Ln (/) is natural logarithm, TMS is the time multiplier setting and A, B, C, D and k are constant parameters.

In Equations 2.6 and 2.7, authors provided an alternative kind of voltage depended property presented in (Jamali & Borhani-Bahabadi, 2017c). The construction of the N-SC targeted to enhance recloser-fuse coordination in a system of distribution inclusive of DG units. The presented method has identical limitation and benefits with (Jamali & Borhani-Bahabadi, 2017a). It is shown that the voltage variation caused to changes in the proposed characteristic.

$$X = Vf \times (1 - \mathrm{Vf}) \tag{2.6}$$

$$t = X \times \left[\frac{28.2}{\left(\frac{Isc}{Iset}\right)^{2}\left(\frac{1}{e^{1-Vf}}\right)^{2}} + 0.1217\right] \times TMS \tag{2.7}$$

where t is the recloser operation time, X is the variation voltage, Vf is the recloser fault voltage, Isc is the short circuit fault current, $Iset$ is the current setting and TMS is the time multiplier setting.

A varying voltage-based N-SC, that is provided Equation 2.8, was indicated in (Agrawal, Singh, & Tejeswini) (Tejeswini & Sujatha). The characteristic equation was identical to NSCs proposed in (Khaled A. Saleh et al., 2015), but for the use of the voltage they applied the logarithmic function. Therein, they added the determined voltage value to the characteristic equation utilising its per unit value and the k parameter can be used to monitor the voltage contribution.

$$t = \left(\frac{1}{1-(\log Vf)^{C}}\right)^{k} \left[\frac{A}{\left(\frac{Isc}{Ip}\right)^{B}-1}\right] \tag{2.8}$$

where *t* is the operation time. Vf is the per-unit of the phase fault voltage magnitude, Isc is the short circuit current. Ip is the pickup current, Log (/) is logarithmic function, TMS is the time multiple setting of relays and *A*, *B* and *k* are constant parameters.

It can be obvious that the main NSCs disadvantage in (Khaled A. Saleh et al., 2015), (Jamali & Borhani-Bahabadi, 2017a), is that the approaches in existing industrial OCR cannot be applied. Furthermore, alongside the fault currents problem, there is a new requirement, which is measuring the fault voltage that will boost the complexity of problems.

2.6.2 Non-standard characteristics: Logarithmic Function Curves:

To improve the selectivity and sensitivity in the OCR coordination and avoid the IEC standard curves disadvantages, some researchers heading for another curve based on NSCs, which is logarithmic function curve. Originally, authors in ref (Keil & Jager, 2007) introduced a novel proposal that achieved a significant reduction in tripping times compared to those reported in the above-mentioned methods using the IEC standard curves. Further details will be provided in the next chapter.

Chapter 3: Literature Review

Researchers still explored the use of unconventional strategies of the OCRs coordination to mitigate the shortcomings of the standard method for providing reliable power system protection and reducing the overall relay operational time. In recent decades, as discussed in Chapter 2, numerous research studies have examined the issue of coordinating OCR systems, resulting in a variety of proposed solutions. This chapter provides a literature review of the relevant topics and studies that identify the research gaps addressed in this thesis. The primary objective of this thesis is to introduce nonstandard curves that overcome the limitations of previous curves while optimizing existing theories.

3.1 Literature Review of Relay Characteristics

In ref (Henville, 1993), hybrid characteristics was proposed by combining inverse and definite time ground overcurrent elements. The proposed method was used the standard IEC curves and applied in radial DN. Using hybrid characteristics can lead to dynamic miscoordination, requiring careful implementation. Nonetheless, technology is available for enabling dynamic coordination. If commercially available relays incorporated this technology, hybrid characteristics could be more extensively applied to reduce tripping time overcurrent protection of radial DNs. This study did not apply the proposed approach in the radial DN with the existence of DGs. Then, the need of more methods applicable in DNs with presence of DGs.

The study proposed in Chapter 2 (Khaled A. Saleh et al., 2015), introduced a novel time-current-voltage relay characteristic suitable for DOCRs within a meshed DN when DG units are present. This new characteristic leverages the magnitude of fault voltage along with the current to establish the DOCRs' operating time as shown in Equation 2.3 in Chapter 2. Besides the standard relay settings, a third setting aimed at adjusting the impact of voltage on relay operating time has been introduced. This new setting can be a single common value for all DOCRs, or each DOCR may have its own optimal value. The protection coordination challenge is framed and resolved by taking into account both the conventional and the novel relay characteristics. The findings indicate that, for each DOCR in a meshed distribution network, applying the proposed time-current-voltage characteristic can notably reduce the total relay operating time, regardless of the presence or absence of synchronous-based and inverter-based DG.

A novel relaying scheme that incorporates a developed time-current-voltage characteristic is introduced for coordinating reclosers and fuses in DNs with DG in ref (Jamali & Borhani-Bahabadi, 2017b). This proposed scheme can be utilized in modern reclosers equipped with microprocessor-based relays. The relaying scheme employs the voltage magnitude of the faulted phase(s) at the recloser's location alongside the fault current magnitude as it presented in Equation 2.4 in Chapter 2. It is shown that the new scheme can enhance the maximum DG capacity within the radial Iranian network compared to the standard characteristic and a recently proposed method. the proposed scheme effectively addresses the limitations of traditional methods for the fuse-saving strategy. Additionally, it is straightforward and economical compared to recent approaches that necessitate expensive communication links or FCLs.

The main disadvantage of the NSCs methods in refs (Khaled A. Saleh et al., 2015) and (Jamali & Borhani-Bahabadi, 2017b) is that the approaches in existing industrial OCR cannot be applied. Furthermore, alongside the fault currents problem, there is a new requirement, which is measuring the fault voltage that will boost the complexity of problems.

A piece-wise linear (PWL) characteristic has been proposed in (Ojaghi & Ghahremani, 2016) to preserve the CTI between the primary and the backup relay pairs for the entire range of the fault current. The successive straight lines were joined together to formulate the new characteristic curve, and a tabular format is used to adjust the curve for the existing industrial relays. In contrast to standard characteristics, this characteristic sustains a CTI between primary and backup relay pairs, thus preventing unnecessary increases in time delay for the backup relays. Furthermore, utilizing this characteristic allows the OCR to stabilize against high initial load currents without affecting its performance against higher fault currents. In radial, ring, and double-side-fed networks, formulating this characteristic does not require complex mathematical computations. Once the necessary data is provided, the table or graph of the characteristic can be easily and directly offered.

Other coordination approaches that involve employing user defined characteristics for inverse time OCRs are suggested, such as adjusting the shape of the standard curve that by changing constant parts of the standard IEC equation to variables to avoid miscoordination between OCRs and enhance the reliability of power system protection that by reducing the overall of the relay tripping time. In ref (Sharaf, Zeineldin, Ibrahim, & Essam, 2015), authors introduced a novel coordination strategy for time inverse OCRs, allowing users to define a relay time/current characteristic distinct from the standard predefined curves (NI, VI, and EI) that best matches their system’s configuration and conditions. This is accomplished by treating the A and B constants—responsible for shaping the characteristics—as adjustable parameters, in addition to the conventional TMS and Ip, thereby leveraging the extensive capabilities offered by digital and numerical relays, it represents by Equation 3.1 as follows.

$$\text{tj} = \left[\frac{\text{Aj}}{\left(\frac{Isc}{Ip}\right)^{\text{Bj}} - 1}\right] \times \text{TMSj} \tag{3.1}$$

where tj is the operation time, Aj is the constant for relay characteristic, Bj is the constant representing inverse time type, $TMSj$ is the relay time multiple setting, Isc is the short circuit current and Ip is the pickup current setting. Usually, Aj and Bj can have one of the four fixed standard values shown in Table1.1 in Chapter 1. The constants A and B have been selected to range from a minimum of 0.14 and 0.02 to a maximum of 1 and 13.5, respectively, which correspond to the standardized values of the IEC 60255 standard for the very inverse time-current relay characteristic.

The protection coordination challenge is addressed as a nonlinear optimization problem, where four optimal settings are established for each relay. The proposed design is evaluated on the distribution system section of the meshed benchmark IEEE-30 bus system. Simulation findings demonstrate the effectiveness of the proposed coordination strategy with the four-settings inverse time OCR, compared to the traditional relay with only two adjustable settings, both in the presence and absence of DG and across varying fault locations in the coordination design. This innovative strategy can result in a reduction of overall relay operating time by approximately 50%. Additionally, the results indicate that the design can achieve decreased relay operating times regardless of DG size and location, and irrespective of the number and positions of fault points considered during the system's relay coordination design.

To mitigate and avoid the limitations in the classic characteristics such as the inverse time–current characteristics of MG systems, a new investigation addressed the issue of miscoordination within multi-source interconnected meshed DNs incorporating DGs. This NSC based on adding the auxiliary variable to the conventional OCR tripping time equation is presented by (A Yazdaninejadi, Nazarpour, & Golshannavaz, 2017), which aims to achieve a fast protection scheme based on well-defined time–current characteristics (TCCs). All these auxiliary variables are measured as coordination constraints. The Equation 3.2 represents this NSC method as follows,

$$t = \left[\frac{\mathrm{Aj}}{\left(\frac{Isc}{Ip}\right)^{\mathrm{Bj}}-1} + Cj\right] \times \mathrm{TMS} \tag{3.2}$$

where Aj, Bj and Cj are auxiliary variable, taking into account the constraints Aj, Bj and Cj , the maximum boundaries for A, B, and C are set at 13.5, 1, and 1 respectively. Meanwhile, the parameters are assigned minimum boundaries of 0.14, 0.02, and 1 respectively.

Research demonstrated that traditional methods are associated with longer relay operation times. In contrast, the newly proposed method reduced the overall operation times. Additionally, discrimination times remained close to zero. Consequently, it facilitated a rapid-response fault clearance method. Due to the limited flexibility of conventional methods, a high number of miscoordinations between primary and backup pairs were noted. Nevertheless, it was significantly lessened by applying the proposed method. Moreover, the proposed method successfully met coordination requirements even with substantial DGs penetration. It accurately considered both the installation location and size of DGs. A similar observation was made for faults with varying impedances. However, it is inapplicable in existing industrial OCRs.

In the same context, authors in ref (Karegar, 2017) proposed a new method for microgrid protection. Relay parameters are incorporated into the optimization problem variables in what is referred to as the curve selection approach. The coordination of curves is influenced by the network and fault currents detected by relays, whereby some curves achieve more reliable coordination. The most precisely defined curve does not breach CTI limits and has the shortest OCR operation time compared to other curves. This is achieved by coefficients variable A and B, which are selected from a given range rather than fixed, predetermined values, as $0.14 \leq A \leq 80$ and $0.02 \leq B \leq 2$. Network topology and specifications are essential for obtaining optimum values of A and B, varying from one network to another.

$$t = \left[\frac{\mathrm{Aj}}{\left(\frac{Isc}{Ip}\right)^{\mathrm{Bj}}-1}\right] \times \mathrm{TMS} \tag{3.3}$$

where t is the operation time, Aj and Bj are constant parameters, TMS is the time multiple setting, Isc is the short circuit current and Ip is the pickup current setting.

The proposed approach is implemented in radial and meshed DNs. The outcomes showed that the OCR curve selection facilitated quick fault detection, particularly in microgrids with minimum fault currents in islanded mode, ensuring that the relays function correctly in both modes. For determining the optimal curve, FCL impedance, and relay settings, a hybrid GA-LP technique is employed as an optimization technique.

The study has been proposed in ref (Kılıçkıran, Akdemir, Şengör, Kekezoğlu, & Paterakis, 2018), introduced an unconventional relay characteristic that incorporates both current and voltage measurements. It also describes a protection strategy where relays function with a double characteristic, featuring separate relay characteristics for primary and backup functions. There are two differences between the proposed equation and the IEC conventional equation can be identified as changing the constant coefficients to adjustable coefficients and the voltage measurement. Int this research, the comparisons focused solely on the IEC standard characteristic. The proposed equation can be illustrated as below,

$$t = \left[\frac{\log(Vfj + \mathrm{Aj})}{\left(\frac{Isc}{Ip}\right)^{\mathrm{Bj}} - 1} + Cj \right] \times \mathrm{TMS} \tag{3.4}$$

where Aj, Bj, and Cj are variables that adjusted to accomplish protection coordination. Given that the OCRs can measure voltage, the equation includes a parameter, Vfj, representing the per-unit voltage of the bus where the relay is connected, Log (/) is logarithmic function

The suggested approach is evaluated through a meshed distribution grid with presence of the DGs. The findings indicate that using the proposed scheme successfully achieves protection coordination, regardless of the varying locations and capacities of the DG units. Besides ensuring dependable protection, further reduction has been achieved on the total relay operation time employing both the proposed characteristics and the protection scheme. In a future study, the authors plan to explore the development of unique characteristics for each fault type to enable adaptive relay operation.

For obtaining the optimal coordination of OCRs in meshed networks, the piece-wise linear characteristic (PWLC) has been evolved as a novel method (Azari et al., 2022). It used variables coefficients, namely A and B, of the PWLCs of the OCRs for adjusting purposes and obtaining a more flexible TCC with the NI standard; however, the proposed method was not tested by changing the location and the size of the DGs to evaluate their effect on the performance of the proposed approach. There are some researchers who have considered the SCs' constant parameters as variable set points, which is another NSC format. This NSC format aims to develop flexible TCCs by creating necessary CTI for the range of the entire fault current between the primary/backup pairs of the relay.

It's worth mentioning that the above-mentioned nonstandard methodologies demonstrate the assessment of dynamic performance compared to the traditional approach. The dynamic models enhance and improve the coordination operation principles beyond the standard relay characteristics. However, increasing the number of variables in the equations can boost the complexity of the computing process and decrease its speed.

Besides the NSCs based on using dynamic coefficients on IEC curves. To improve the selectivity and sensitivity in the OCR coordination and avoid the IEC standard curve disadvantages, some researchers are heading for another curve based on NSCs, which is a logarithmic function curve. Originally, authors (Keil & Jager, 2007) introduced a novel proposal that achieved a significant reduction in tripping times compared to SCs and NSCs that have been mentioned above. This logarithmic function equation can be shown below.

$$t = \left(5.8 - 1.35 \times \log_e\left(\frac{Isc}{Ip}\right)\right) \times TMS \tag{3.5}$$

where t is the operation time, TMS is the relay time multiple setting, Isc is the short circuit current and Ip is the pickup current setting, $\log_e$ (/) is logarithmic function and TMS is time multiplier setting. The logarithmic function advance method will be introduced in detail in Chapter 4.

The outcome appeared a significant decrease in the tripping time compared to traditional time grading and maintained the selectivity between the OCRs without communication links by using a new nonstandard tripping characteristic based on logarithmic function. However, the proposed scheme did not investigate the impact of DG units on distribution grids.

Authors in refs (Alasali, El-Naily, Zarour, & Saad, 2021)-(F. Alasali, E. Zarour, W. Holderbaum, & K. N. Nusair, 2022b) improved the proposed coordination scheme based on logarithmic function that illustrated in Equation 3.5. Proposed approaches were applied in radial networks with different optimization techniques. The nonstandard time–current characteristics are created by using the logarithmic function and constant coefficients, which lead to significantly minimizing the overall operational time on maximum fault currents, but it showed limited behaviour on minimum fault currents. Table 3.1 shows an overview of the literature review that has been introduced above.

Table 3.1: A Literature Review Comparison Analysis for Protection the Radial and Meshed Networks

Ref.	Coefficient Types of Coordination Protection Scheme		Number of Variables Coefficients			Modes of the Operation			DNs Types		Curve Used	
	Constants	Variables	One variable	Two variables	Three variables	Without DGs	Grid-connecting	Islanding	Radial	Meshed	IEC NI standard	Logarithmic function
(Henville, 1993)	✓	×	×	×	×	✓	×	×	×	✓	✓	×
(Khaled A. Saleh et al., 2015)	✓	×	×	×	×	✓	✓	×	×	✓	✓	×
(Jamali & Borhani-Bahabadi, 2017b)	✓	×	×	×	×	✓	✓	×	✓	×	✓	×
(Kılıçkıran et al., 2018)	×	✓	×	×	✓	×	✓	×	✓	×	✓	×
(Keil & Jager, 2007)	×	✓	×	✓	×	✓	×	×	✓	×	×	✓
(A Yazdanineja di et al., 2017)	×	✓	×	×	×	×	✓	×	✓	✓	✓	×
(Ojaghi & Ghahremani, 2017)	✓	×	×	×	×	-	-	-	✓	✓	✓	×
(Azari et al., 2022)	×	✓	×	✓	×	✓	×	×	×	✓	✓	×
(Sharaf et al., 2015)	×	✓	×	✓	×	✓	✓	×	×	✓	✓	×
(Karegar, 2017)	✓	×	×	×	×	×	✓	✓	✓	✓	✓	×
(Alasali et al., 2021)	✓	×	×	×	×	✓	✓	✓	✓	×	×	✓
(F. Alasali, E. Zarour, W. Holderbaum, & K. Nusair, 2022a)	✓	×	×	×	×	✓	✓	×	✓	×	×	✓
Proposed Approach	×	✓	✓	×	×	✓	✓	✓	✓	✓	×	✓

As shown in Table 3.1 above, in refs (Henville, 1993), (Khaled A. Saleh et al., 2015), (Sharaf et al., 2015), (Jamali & Borhani-Bahabadi, 2017b), (A Yazdaninejadi et al., 2017), (Ojaghi & Ghahremani, 2017), (Karegar, 2017), (Kılıçkıran et al., 2018) and (Azari et al., 2022), the proposed nonstandard curves were based on the IEC curve. Authors in refs (Henville, 1993), (Khaled A. Saleh et al., 2015), (Jamali & Borhani-Bahabadi, 2017b; Ojaghi & Ghahremani, 2017) and (Karegar, 2017) focused on the use of nonstandard IEC curves based on voltage and other parameter with keeping the constant coefficients on the curve as constants. Whereas authors in ref (Sharaf et al., 2015), (A Yazdaninejadi et al., 2017), (Kılıçkıran et al., 2018) and (Azari et al., 2022) proposed the nonstandard characteristics based on assuming variable coefficients instead of the constant coefficients as that shown in detail above. In addition, a different nonstandard curve known as logarithmic function curve have been proposed by (Keil & Jager, 2007), (Alasali et al., 2021) and (Alasali et al., 2022a). This curve demonstrated its dependability and effectiveness by reducing overall tripping times and preserving the selectivity between OCRs in radial networks with DGs present. However, it exhibited certain limitations in its performance with the minimum fault current. The proposed approach filling this gap by using variable coefficient that makes the curve more flexible, which it can improve the performance of the logarithmic function curve with the minimum fault currents. In addition, using only one variable coefficient in the logarithmic function equation does not increase the curve constraints compared to those that utilize dynamic variables in the IEC curves mentioned above. Therefore, the proposed method provides two advantages: it improves selectivity between OCRs settings during minimum and maximum fault modes and simplifies the equation by employing just one variable coefficient. Furthermore, the proposed approach applies in radial and meshed DNs and it evaluates using 3Φ fault in different topologies with and without DGs.

3.2 Literature Review of Optimization Methods

As mentioned in Chapter 2, optimization methods are utilized to avoid the limitation of classical methods due to the integration of DG units in distribution systems. As indicated in Table 2.1, numerous researchers aimed to design hybrid heuristic algorithms to enhance the efficacy of global optimization algorithms. The development of hybrid heuristic algorithms will boost the advantages of conventional techniques considerably. The hybrid heuristic algorithms are usually robust and efficient in comparison with the basic editions of the algorithms that are hybridized since they can profit from the benefits of various heuristic algorithms (Ali, Awad, Suganthan, Duwairi, & Reynolds, 2016)-(Gao et al., 2012)-(Khalilpourazari & Pasandideh, 2016)-(Khalilpourazari & Khalilpourazary, 2017) Many investigators intended to create hybrid heuristic algorithms to develop more effective international optimization algorithm.

The water cycle algorithm (WCA) is initially introduced by (Eskandar, Sadollah, Bahreininejad, & Hamdi, 2012). WCA is a heuristic algorithm that imitates the nature water cycle. It is based upon robust conceptual bases which allow the algorithms to address the issues of optimization effectively. While The moth flame algorithm (MFO) approach is applied by using this action and mathematical (Mirjalili, 2015). Moths are very similar to butterflies, as a group of insects. One of the moths' most remarkable behaviors is their peculiar approach to navigation. To travel long distances in a straight line, they fly by maintaining a fixed angle toward the moon. The name of this successful method is transverse orientation. The efficacy of the transverse orientation depends strongly on the distance from the source of light. For example, when the source of light is near the moth, the moth starts moving around the light in a spiral direction. Finally, this spiral fly course converges the moth to light (Khalilpourazari & Pasandideh, 2017). The WCA has tremendous ability to explore the space for solution in case of problem. In the WCA, streams and rivers are updating their position toward the sea, and this method allows the search agents to refresh their position regarding the best solution. Therefore, the WCA suffers from the lack of an effective director to carry out exploitation. Alternatively, MFO 's ability to use its spiral motion performs very well in exploitation but cannot adequately explore the solution area. This is because each moth updates their position toward their respective flame. Furthermore, the search agents do not share the details of the best solution found so far by the MFO. The WCA's first change is using the moths' spiral movement to monitor stream and river location. The fundamental WCA's syncing procedure only considers the space between the stream and a river when modifying a stream 's position. In other words, in the space between the stream and its corresponding river, the next stream location will be in. Conversely, the MFO algorithm's updating process helps the moths to change their location anywhere around their respective blaze. Allowing streams and rivers to update their position using the moths' spiraling motion greatly increases the HWCMFO's opportunity to exploit.

The inspiration behind this study is to investigate an effective WCA and MFO hybridization that can profit from both algorithms' benefits in HWCMFO, which is inspired by (Khalilpourazari & Khalilpourazary, 2019). The HWCMFO can provide substantially stable and effective approaches to complicated optimization problems. Such one of these problems is the MG protection coordination problem. Thus, applying the HWCMFO can ensure the selectivity between relays and obtained optimized TMS relays settings for the MG.

The proposed method considers and improves the proposed method introduced by Naily, Saad, Hussein and Mohamed in ref (El-Naily, Saad, Hussein, & Mohamed, 2019). Authors proposed N-SC in the industrial OCR that by extension the PSM, they consider the maximum value of PSM as $PSM_{\max}$ 100 times of the pickup current of the relay for complying with extreme fault currents caused by integration DGs, they obtained proper tripping times during different faulty conditions for several topologies in the MG, therefore, improving the protection coordination performance has been achieved. The authors in (Sergio Danilo Saldarriaga-Zuluaga, Jesús María López-Lezama, & Nicolás Muñoz-Galeano, 2020a) improved the previous proposed method which consider $PSM_{\max}$ as variables ranging instead of parameters; the range of $PSM_{\max}$ is between α PSM and β PSM. The authors select α and β values as 5 and 100 respectively, the results appear an appropriate coordination of directional OCRs in MGs that with a lower time than conventional approaches.

The proposed approach in Chapter 5 investigates an effective of a new hybrid optimization technique known as HWCMFO algorithm, our proposed approach adeptly determines optimal relay settings for different operational modes in radial network compared to heuristic techniques that reported in the literature review. It ensures selectivity between OCRs within the shortest operational timeframe possible. It shows that the performance of a numerical protection device and a hybrid optimization technique can be used for exploring the non-standard and user-defined OCR characteristics to ensure adequate coordination of MGs protection.

3.3 Discussion and Summary

Integration of DG into the grid is a major issue for modern power systems. More energy efficiency and lower emissions are only two of the numerous benefits of DG, but it also creates some difficulties for the power grid's safety mechanisms. Due to the variable and unpredictable nature of DG, protection coordination might become more difficult to implement. To overcome these obstacles, researchers have tested different relay coordination techniques as shown in Chapters 2 and 3 and some of them summarised in Tables 2.1 and 3.1.

The effectiveness of these new optimization algorithms and relay coordination schemes has been demonstrated in several studies. However, Table 3.1, presents some drawbacks or imperfect points that create a research gap. Therefore, there is a significant need to find an alternative to the IEC NI standard curve for more flexible and dynamic protection coordination schemes for radial and ring DNs and MGs, especially at far-end faults (minimum faults). In addition, ensuring the CTI selectivity between OCRs and minimising the trip time in different operating modes are required. To fill this discussed research gap, optimal OCR coordination based on a new NSTCC with dynamic coefficients to provide a fast and reliable response in different network scenarios is proposed with details in Chapter 4. Two optimization techniques, namely GA and GSA–SQP algorithms, have been applied with this proposed method, as well as the proposed approach, which is applied in the IEC benchmark and IEEE-9 bus as radial networks as well as IEEE-9 bus and IEEE-30 bus systems. This novel NSTCC is the first contribution to the present thesis. Secondly, as an optimization task to present the OCR coordination problem, an artificial intelligence hybrid algorithm based on HWCMFO has been used as a novelty and applied as an optimization technique with a new non-standard characteristic approach (N-SCA) in the IEC benchmark MG to present its impact in industrial relays and contribute towards solving the OCRs coordination problem in terms of CTI between primary and backup relay pairs and overall operation time in the presence of the DGs in the DNs. Furthermore, our method demonstrates accelerated convergence towards the global minimum within a short computational time compared to alternatives. Chapter 5 describes and analyses the proposed N-SCA based on HWCMFO algorithm in detail.

Chapter 4: Novel Optimal Nonstandard Tripping Protection Scheme for Microgrid Systems

4.1 Introduction

Integration of renewable energy sources such as solar into the electrical infrastructure has gained momentum as the world endeavours for a more sustainable energy future. However, this transition has brought with it a unique set of power protection challenges. The traditional protection scheme in distribution systems, which was designed for a large centralised power generation model, has difficulty accommodating the variability and unpredictability of renewable energy sources. The increasing penetration of DGs into the grid has resulted in significant changes to the system's fault characteristics, which can compromise the network's dependability, stability, and safety. The fault characteristics of these systems differ significantly in the presence and absence of DGs, further exacerbating the issue. With a growing number of DGs interconnected within the network, the gap between the minimum and maximum levels of fault current has significantly widened. As a result, relying on traditional protection settings may prove inadequate to meet the system's requirements for sensitivity, speed, and selectivity, rendering the system vulnerable to potential failures. Consequently, guaranteeing effective power protection is now essential for maximising the potential of renewable energy sources and achieving a sustainable energy future. There is a need to have more innovative and sophisticated protection mechanisms that can adapt to the dynamic and unpredictable nature of DGs and ensure the stability and reliability of distribution systems.

Most of the RESs such as wind turbines and PV systems have been used power-electronic inverters for connecting to the MG system. In MGs, the IDGs such one has been used in the protection; however, the inverters have a limitation of the generated fault current, 150% of the current rating (El-Naily et al., 2020). This makes the conventional overcurrent devices either stop responding or respond at a much larger operating time (Jamali & Borhani-Bahabadi, 2017b). New challenges and opportunities appeared due to the growing wind turbine energy share, which led to a preference in the use of doubly fed induction generators (DFIG) over fixed-speed wind turbine systems. The connection of the wind farm to the network contains a low-voltage ride-through (LVRT) ability that is the most important requirement. Furthermore, owing to the DFIG essentially working the same to SDGs, power factor control might be applied at a reduced cost (Din, Zhang, Xu, Zhang, & Zhao, 2021). The contribution of fault current from SDGs can rise to about ten times the current rating (Kida et al., 2020). In general, the fault currents in MGs are dependent on the ratio of ratings between SDGs and IDGs. Likewise, the fault current contribution ability (FCCA) of IDG is very low (110%). This means that the mode used is the islanding mode; the OCRs may be unsuccessful in the case the MG only has IDGs. This is because the ratio of IDGs to SDGs in the mixture causes difficulty in the protection coordination as well as low fault current. In general, the DOCR aims to deal with bidirectional flow of power failures evenly. In addition, if the MG is able to operate in the loop and radial topology, the relay coordination and the detection scheme under primary fault becomes complex using different types of DGs. In order to handle the protection challenges in MGs, a fast and robust optimal protection scheme is required. The main objective of this article is to present an optimal and fast coordination scheme that minimizes OCR operational times for all operation and fault modes in MGs.

To improve the selectivity and sensitivity in the OCRs coordination and avoid the NI standard curve disadvantages, an optimal coordination scheme based on nonstandard time-current characteristics is presented in (Alasali et al., 2021)-(Alasali et al., 2022a). However, the nonstandard time–current characteristics are created by using the logarithmic function and constant coefficients, which lead to significantly minimizing the overall operational time on maximum fault currents, but it showed limited behaviour on minimum fault currents. There are some drawbacks or imperfect points as seen in the literature chapter that make a research gap, as discussed in Chapters 2 and 3. There is a significant need to find an alternative curve instead of the NI standard curve that more flexible and dynamic protection coordination scheme for radial and ring DNs and MGs, especially at far-end faults (minimum faults). In addition, ensuring the CTI selectivity between OCRs and minimizing the tripping time in different operating modes are required indeed. For filling this research gap, an optimal OCRs coordination based on a new nonstandard time-current characteristics (NSTCC) with dynamic coefficients to provide a fast and reliable response in different network modes is proposed. An optimization task to present the OCRs coordination problem has been solved by applying two optimization techniques, namely: GA and GSA-SQP algorithms. This chapter aims to propose a novel approach to enhance the performance of power protection systems by integrating DG units and introducing a NSTCC protection technique. The proposed method addresses the constraints of the existing model and is proven to achieve a significant reduction in total OT without miscoordination records. In the optimum coordination approach for OCR, the proposed NSTCC is utilized to reduce the total OT compared to traditional SCs and other NSCs presented in the literature. Moreover, the new optimal scheme based on NSTCC is developed with a lower number of constraints compared to the optimal coordination in the literature. This approach achieves the optimal solution with minimum computational costs and requires no communication between OCRs. The proposed approach provides adequate robustness to OCRs coordination while reducing the demand for communication infrastructure and making a significant reduction in computational cost. The sensitivity of the proposed optimal scheme is demonstrated by comparing the results of the NSTCC and the standard curves under different testing and MG operation modes. Furthermore, a comparison analysis is provided for the proposed optimum coordination approach under various faulty conditions for two DN types, radial and meshed networks. The results demonstrate the superiority of the proposed approach, especially for minimum fault in islanding mode.

In summary, this chapter presents a novel approach to enhance the performance of power protection systems with the integration of DG units and NSTCC technique. The proposed method achieves a significant reduction in total OT without miscoordination records, and the new optimal scheme based on NSTCC requires no communication between OCRs while achieving the optimal solution with minimum computational costs. The sensitivity improvement for the proposed optimal scheme is also demonstrated, and the results prove the proposed approach's superiority over others, especially for minimum fault in islanding mode. The findings of this chapter have been published in a journal, Energies, by the author of this thesis. The paper is titled "Innovative Optimal Nonstandard Tripping Protection Scheme for Radial and Meshed Microgrid Systems," and it demonstrates the effectiveness of our proposed protection scheme in comparison to other benchmarking methods. The main contribution in this paper is from S. Abeid as first author including conceptualization, methodology, investigation, software, validation, formal analysis, resources, visualization, writing—original draft preparation, writing—review and editing.

4.2 Problem Description: Illustration-Based Analysis

The MGs with RESs must be protected to ensure that the operating conditions are reliable and safe (Darabi, Bagheri, & B. Gharehpetian, 2020)-(El-Naily et al., 2019). The coordination of OCRs in distribution systems can be done easily, especially those in the radial structures and weakly meshed MGs (Chabanloo, Maleki, Agah, & Habashi, 2018)-(Aghdam, Karegar, & Zeineldin, 2018). However, in the interconnected and meshed systems, each of the given relays acts as backup relays, where several delays are set as backup for one relay. Figure 3.1a shows a one-line illustration of the DN with three distribution lines (DL_1, DL_2, DL_3) protected by overcurrent relays (R_1, R_2, R_3). Figure 4.1a illustrates the OCRs coordination from the side of the load to the source. For instance, a fault at the F1 point results in R_1 primary relay and R_2

backup relay. If the R_1 is unable to detect the fault or tripping delays, the R_2 will have time delays. Figure 4.1b shows the effect of the fault location on the fault current. It can be noticed that the fault current is increased whenever closer to the main source. Figure 4.1c is an illustration of the OCRs coordination curves in three modes, which are a conventional network (that has no RESs), power network with DG and islanding mode. Ordinarily, the OCRs operating time, in no DG case, is high because there is a CTI ranging from 0.2-0.5s, stressing the network equipment, possibly causing the relay to get into a the precise time region, more so for maximal fault modes (when faults occur near the source) (Sergio Danilo Saldarriaga-Zuluaga, Jesús María López-Lezama, & Nicolás Muñoz-Galeano, 2020b)-(El-Naily et al., 2020)-(El-Naily et al., 2019).

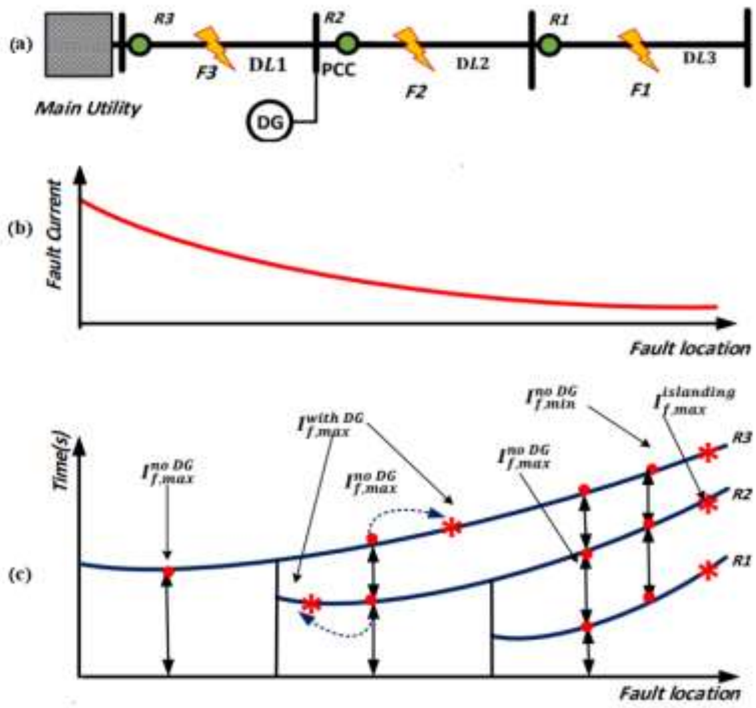


Figure 4.1: (a) The single line diagram of the DN with DG under three fault modes, (b) the relationship between fault current and fault location and (c) the miscoordination between the primary and backup relays and fault characteristics with and without the DG

The conventional protection scheme experiences more challenges because of the different fault characteristics between the distributions systems in the presence and absence of RESs. The rising number of sources of renewable energy in the network has widened the variation range between the minimum and maximum levels of fault current. Consequently, the calculation of the traditional protection setting will not meet the system requirements of the main protection: sensitivity, speed, and selectivity (Jamali & Borhani-Bahabadi, 2017b)-(Meskin et al., 2015). For instance, when the fault occurs at F2 point for a distribution grid that has DG as illustrated in Figure 4.1c, the fault current value will go up in the R_2 primary relay and go down in the R_3 backup relay, resulting in a time delay causing disconnection or OCRs coordination failure (N. Hussain et al., 2020)-(El-Naily et al., 2019). Figure 4.1c illustrates the effect of the connection between the DG and the fault current, I_f. One, R_2 maximum fault current for DG power network, $I_{f,max}^{with\,DG}$, goes up while it goes down for R_3 when comparing with the maximum fault current during the absence of DG, $I_{f,max}^{no\,DG}$. Generally, the fault characteristics of a DN with DG have been altered because of loading/generation level changes, variations in the network typology, islanding, fault point resistance, and the location of the fault point in relation to the main relay. Alterations of the fault current will result in OCRs miscoordination, for instance, the R_3 will possibly does not operate once there is a fail on R_2 for the minimal fault current, $I_{f,max}^{islanding}$, in which the current value will be reduced compared with the distribution network in the absence of DG, $I_{f,min}^{no\,DG}$. For the islanding case, the fault current is so low making its detection on the basis of the conventional scheme difficult (Darabi et al., 2020)-(N. Hussain et al., 2020). As a result, the conventional coordination and protection scheme will not have the capacity to handle the issue, which makes the development of a new time-current characteristic to address the challenges of DG protection very important. Furthermore, a DG-equipped system of protection for DN is needed to respond to the faults in all modes of DG operation e.g., grid and islanded. This study proposes and develops various quick and intelligent schemes of protection and coordination. The coordination schemes' main objective is calculating the PSM and coordination curves which reduce the tripping time of OCR.

The coordination between the OCRs in the traditional protection scheme is generally obtained with the assumption that the conditions and network parameters during a fault will remain constant. According to Figure 4.1c, Equation 4.1 describes the CTI between the t for the primary relay and backup relay for short circuits that occurs for instance at F2 point (El-Naily et al., 2020)-(Meskin et al., 2015)-(El-Naily et al., 2019). The CTI presentation is such that the time of coordination between the backup relay, t_{R3} , and the main relay, t_{R2}, is equal to or more than the designated CTI.

$$t_{R3} - t_{R2} \geq CTI \tag{4.1}$$

Figure 4.1c illustrates how DG addition to the distribution grid affects the scheme of coordination protection (Adelnia, Moravej, & Farzinfar, 2015)-(Coffele, Booth, & Dyśko, 2014). The fault current variations will result in a CTI between the primary relay and backup relay that is lesser than the chosen CTI causing a miscoordination. In general, numerical OCRs have the capability to update and modify the time operating characteristics based on the real time measurements. In this proposed approach, the numerical OCRs provide the ability of using different time operating characteristics such as the standard characteristics (IEC, The American National Standards Institute (ANSI) or generating new non-standard operating characteristics. The proposed non-standard time characteristics in this thesis, NSTCC, aims to minimize the total tripping time and improve the performance of power protection in term of selectivity and sensitivity.

4.3 The Proposed Methodology: Non-Standard Time Current Characteristics

To guarantee selective coordination of the OCRs, the grading time must remain fixed and unaffected by the fault's location within the network or the level of fault current. The suggested unconventional time-current characteristic, utilizing logarithmic function and constant coefficient for all relays, is detailed in Equation 3.5 in Chapter 3, subsection 3.1 (Keil & Jager, 2007) (Alasali et al., 2021)-(Alasali et al., 2022b) and shown as below. The OT will not depend on the fault level or location, enhancing the selectivity of the protection system regardless of fault currents or their positions. Moreover, normal inverse curves typically struggle with identifying the minimal faults.

$$t = \left(5.8 - 1.35 \times \log_e\left(\frac{Isc}{Ip}\right)\right) \times TMS \qquad (3.5)$$

This contribution aims to introduce optimal OCR coordination based on a new NSTCC with dynamic coefficient to reduce the tripping time associated with the value of fault currents that by replacing the constant coefficient 5.8 to a variable coefficient, described as (A), as illustrated in Equation 4.2 below,

$$t = \left(A - 1.35 \times \log_e\left(\frac{Isc}{Ip}\right)\right) \times TMS \qquad (4.2)$$

where *t* is the operation time, A is a variable coefficient that its value changing in optimization process dependent on faults located within the network or the level of fault current, $\log_e(/)$ is logarithmic function, Isc is a short circuit current, Ip is a pickup current and TMS is a time multiplier setting.

The coordination job for the OCRS is achieved by assessing faults positioned near or at the boundary of the protected zone. The initial scenario involves maximum fault currents when the fault is situated close to the protected line. The second scenario pertains to the minimum fault current located distantly or at the boundary of the protected zone. The selection of these two scenarios is made to attain the necessary CTI and encompass the prompt characteristics while raising the relay's operating time with the integration of RESs, as demonstrated in Figures 4.1 and 4.2. Consequently, each OCR in the DNs must ensure the minimum OT at the first point (maximum fault current). The nonstandard tripping scheme (NSS) curve results in a reduced operating time than the standard characteristic, as illustrated in Figure 4.3. Conversely, for the second aspect, the OCR OT is increased for minimal fault currents. Incorporating RESs into the distribution grid causes the OCR tripping time to lengthen at the minimum fault current (islanding current) more significantly compared to a DN lacking RESs. As shown in Figure 3.4, the NSS curve decrease the OCR tripping time, however it showed limits behaviour due to its inflexibility, consequently there is a miscoordination will be record. To fill this gap a NSTCCs with a variable coefficient has been proposed. The adjustable coefficient A in the proposed NSTCC can be controlled during both maximum and minimum fault currents, thus assisting in preventing miss-coordination issues or cases of non-operation.

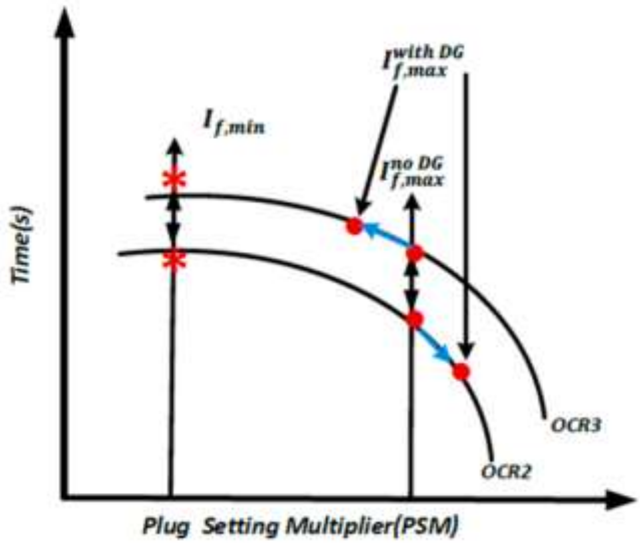


Figure 4.2: A Non-Standard Scheme (NSS) (Alasali et al., 2021)

The proposed NSTCC scheme will be compared to the traditional OCR scheme inverse definite minimum time (IDMT)) (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(Protection, 2006). The Equation 4.2 represents the proposed NSTCC, and the logarithmic function therein (Keil & Jager, 2007) is the basis in this equation.

To ensure OCR coordination selectivity, the grading time should be kept constant and free from the network's location of the fault or the current level of the fault. Equation (4.2) represents the NSTCC for all relays through the use of logarithmic (Keil & Jager, 2007)-(El-Naily et al., 2019) and variable coefficient A with range between 2 and 6.5 that have been obtained Optimizely, the time of grading will not be affected by the degree and point of fault. This will make the selectivity of the protection system better and not dependent on the fault location or current. Moreover, it was difficult for the IEC curves to detect the minimal fault. The NSTCC offers ample area for the detection and coordination of the OCRs in the minimal fault, as illustrated in Figure 4.3 to ensure selectivity without missing the tripping time. The following section describes an optimization task for determining the TMS based on Equation 4.2 that reduces the OT to a minimum. Therefore, coordination on the basis of non-standard tripping characteristics will result in an optimal time of grading in relation to the time of tripping.

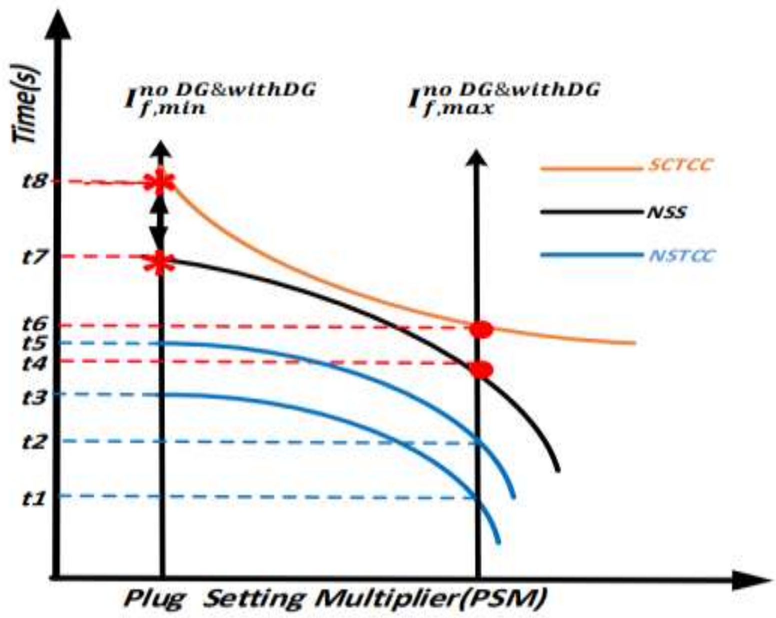


Figure 4.3: A Standard Tripping Current Characteristic (STCC), Non-Standard Scheme (NSS) and Proposed Non-Standard Tripping Current Characteristic (NSTCC)

- *An optimization task for determining the TMS based on the proposed equation*

The effect of adding DGs connected to the DN on the PSM, and the miss-coordination problems appear between OCRs during the maximum and minimum faults is shown in Figure 4.1c. Generally, the ratio between short-circuit current and the pickup current ($\frac{Isc}{Ip}$) is presented as a PSM. This section presents the important of using NSTCC in coordinating the OCRs as illustrated in Figure 4.3. Fault's location near or at the end of the protected zone is the responsible for obtaining the OCRs coordination task. The fault's location is near the protected line (maximal fault current) is covered by the F1 point, while at the end of the protected zone (minimum fault current) is related to the F2 point. The two scenes were selected to attain the required CTI, cover on time attributes, and raise the OCR OT because of the addition of DGs as shown in Figures 4.1 and 4.3.

It can be noticed that in Figure 4.3, the curve of the standard time current characteristic (STCC) has high values of fault currents at both maximum and minimum fault currents. Then, two variables' coefficients A and B for the maximum and minimum faults are required to reduce the tripping time effectively to control the two sides of the curve of the STCC. The researchers in the available literature such as (A Yazdaninejadi et al., 2017)-(Tirumala Pallerlamudi Srinivas & Shanti Swarup, 2020) are used this approach to reduce the operating time, however; this leads to increasing the number of constraints which is another disadvantage. In addition, the authors in (Alasali et al., 2021) have been proposed the curve of the non-standard scheme (NSS) in Figure 4.3, they are used Equation 3.5. Yet, due to the curve is constant as seen in Figure 4.4, the fault currents at minimum faults specially in islanding mode are still a bit high and there is a delay time will lead to appear the miscoordination problem between OCRs. In this work, the NSTCC reduces the tripping time compared with STCC at maximum and minimum faults and non-standard curve in (Alasali et al., 2021) by making the coefficient A as a variable need to have optimal value to achieve the best in reducing the total operating time (OT) for relays. The coefficient A in the proposed NSTCC is controllable at both the maximum and minimum fault currents. For the first point, the minimum tripping time (maximum fault current) must be guaranteed by each OCR in the DN. A lower OT is provided by using the NSTCC curve which is presented by the red doty line compared to NSS that is demonstrated by the black line, as shown in Figure 4.4. With existence of the DG units at the grid at the minimum fault current (islanding current) for the second point, the OCR OT will be increased more than the distribution grid with absence of the DGs. Avoiding any miscoordination problem or not operating cases can be achieved by applied the proposed NSTCC curve, which it minimizes the OCR tripping time as illustrated in Figure 4.4.

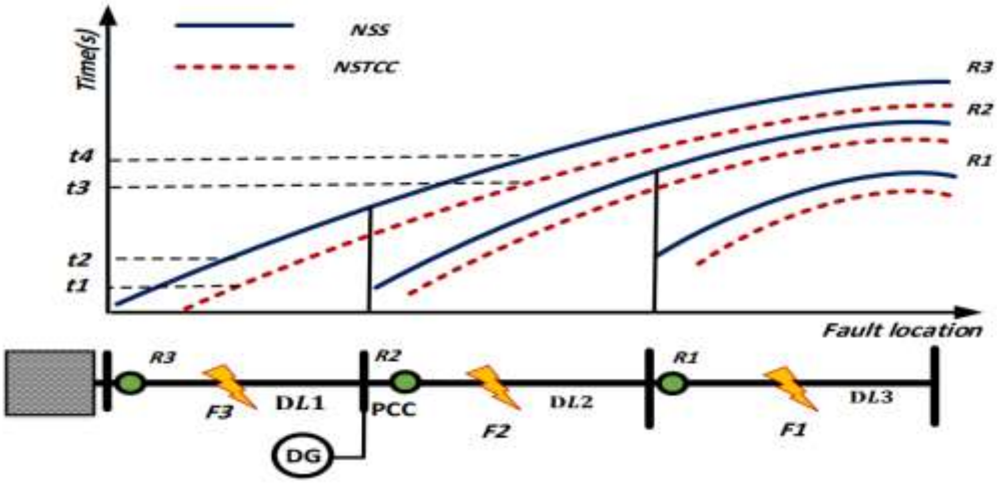


Figure 4.4: A Proposed Nonstandard Time Current Characteristics with variable coefficient A (NSTCC) and Nonstandard Scheme with constant coefficient A (NSS).

4.3.1 Formulating the Coordination Problem:

This study formulates the problem of OCR coordination in a DN that has DGs as a problem of optimization to discover the TMS which minimizes the OCRs OT with insuring the selectivity between the primary relay and backup relay. This part introduces the suggested approach mathematical formula of the optimization for solving the issue of coordination and the performance of the OCR optimization techniques in the MG protection in comparison to the traditional protection approaches.

- *Objective Function*

The main variable for the OCR coordination issue in Equation 4.2 is the TMS which manages the OT of the relay. In this section, the operational time for OCRs and the coordination problem, as described in Section 2, is formulated as an objective function. This objective function (OF) minimizes the overall OT for the main relay and backup relay. The operational time, t, for the total number of relays, x, and total number fault locations, y, is formulated as follows (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019):

$$OF = \sum_{j=1}^{x} \sum_{k=1}^{y} t_{j,k} \tag{4.3}$$

In this work, the NSTCC is used to calculate the tripping time, t, where the coefficient A is controllable at both the maximum and minimum fault currents. Equation 4.3 can be rewritten as following: (To find the optimal A that can achieves the minimum time)

$$\arg\min_{A} \sum_{j=1}^{x} \sum_{k=1}^{y} t_{j,k} \tag{4.4}$$

There are various constraints take into consideration during applied the OF in Equations 4.3 and 4.4 as shown below:

- Coordination Criteria and Selectivity

The selectivity constraint for OCRs coordination is aimed to add operational time delays between the primary and backup OCRs, to minimize power outages on the network on the basis of the location of the fault. The backup OCR will not work except when the main OCR is non-operational. The formulation of the criteria for selectivity can be done on the basis of CTI as constraints of inequality:

$$t_b - t_p \geq CTI \tag{4.5}$$

where t_p represents the OT for primary relays and t_b represents the OT for backup relays. Generally, the CTI (in seconds) is between 0.2-0.5 to guarantee selectivity (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(Aghdam et al., 2018). The value of CTI is dependent on various parameters like relay type and circuit breaker speed. This study works with a CTI from 0.2 to 0.5.

- Relay Setting, Operating Time Bounds:

To keep the limitations of operational time, the constraints should be presented for the minimal and maximal OCR operational time. Nevertheless, the protective relays should have quick operation taking minimum possible time, and if the OCR operation takes more time, there will be damages on the equipment and an unstable power system. The minimal and maximal operation time bounds are shown below:

$$TMS_{min} \leq TMS_j \leq TMS_{max} \tag{4.6}$$

$$OT_{min} \leq OT_j \leq OT_{max} \tag{4.7}$$

where TMS_{min} and TMS_{max} are the minimal and maximal TMS values of relay j and OT_{min} and OT_{max} represent the minimal and maximal time of operation needed for relay, j, (N. Hussain et al., 2020)-(Darabi et al., 2020). The OCRs operation must be within the protection scheme's normal operation time. As a result, the PSM needs to be set in the domain of the minimal and maximal values in the minimum and maximum fault currents in the relay, even with light overloads.

- Proposed Coefficient Setting Bounds:

In this study, the characteristic coefficient in Equation 4.2 is considered as a decision variable, as presented in Equation 4.4. In the previous studies, the inverse curve requires more than one variable coefficient to shift it upwards and downwards (A Yazdaninejadi et al., 2017)-(Tirumala Pallerlamudi Srinivas & Shanti Swarup, 2020), which is leading to greater OCR tripping times with a bit shift in steepness and constraints increasing. Then, the miscoordination between primary and backup relays has existed. For development purpose, the NSTCC is formulated in the Equation 4.2 with just a single variable coefficient, which is A. The NSTCC tends to shift the curve just downwards by changing A_j values, it leads to reduce OCRs tripping times and constraints reduction. As a result, the OCRs coordination performance is guaranteed. The following equation shows the maximum and minimum bounds of the variable coefficient A:

$$A_{min} \leq A_j \leq A_{max} \tag{4.8}$$

where A_{min} and A_{max} represent the minimal and maximal variable coefficient needed for relay j. It has been chosen in this study between 2 and 6.5.

4.3.2 Optimization methods for the OCRs coordination problem:

In section 4.3.2, the OCRs coordination problem in network connected to DGs is presented as an optimization task. This section presents two optimization algorithms, namely: GA and GSA-SQP, as common and new powerful optimization algorithms for solving OCRs coordination problems (Radosavljević & Jevtić, 2016)-(Chabanloo, Maleki, et al., 2018).

- *Genetic Algorithm Optimization (GA):*

For solving complicated optimization problems, the Genetic Algorithm (GA) has been vastly used such an iterative optimization technique (Abdul Wadood et al., 2018)-(Alasali, Haben, & Holderbaum, 2019). The GA technique considers a various applicable solution to obtain the best solution, it proves its worth in the power system protection coordination problem. Using GA in (Chabanloo, Maleki, et al., 2018)-(Alasali et al., 2019) was just for power grids without considered non-standard OCR curves and RESs. In this study, the GA methodology is utilized as innovative iterative optimization model to transact with the overcurrent coordination problem for a distribution system with DGs. Generally, the simulation of the GA is used with a specific population size, where the possible solutions for the proposed optimization problem are described by the population. Chromosome populations or individuals are the possible solutions in the population (Aghdam et al., 2018)-(Adelnia et al., 2015). In the next step, an OF evaluates all solutions for the current generation, this step called fitness function Equation 4.4. The result of the fitness value is mainly associated with the proposed optimization problem for each solution. Creating a new population uses the fitness evaluation that by utilizing selecting, crossing and mutating techniques.

In the present thesis, the general GA flowchart for the proposed ORCs coordination problem is presented in the Table. 4.1. The process of the GA model launches for a profile group of the first-generation OCRs OT. Therefore, for each OCRs OT profile, the Equation 4.4 of the objective function is used as evaluating fitness. Thus, an appropriate selection technique picks the parent OCRs operating time profiles. For the next generation, the selection of the best performance (better fitness value or fittest solution) will be selected. These profiles are chosen for crossover as well as creating a new generation (population), this step known as reproduction. From the profiles of the parent, the common genes of parents are retaining to create the profile of a new generation of the OCRs OT whereas the residual genes are chosen at random from the parents. Nevertheless, the power network or relay constraint might be violated by the child OT profile, consequently, for examination purpose whether the profile of child is under the constraints or not, a feasibility test has been applied. Sometimes the child profiles assigned on the impracticable zone. Then, the solution of the child in this case will be refused and alternative one will be generated by accidentally the uncommon genes until the feasibility of the child profile is realized. At the beginning time and initial iterations, the expectation about child profile, it will be varied and far away from parent OCRs operation solutions. Nonetheless, each iteration the child profiles and parent are nearer to each other as well as the search directs closely to the optimum OCRs operation time profile. Achieving the greatest figure of iterations or reaching the proposed threshold are the goal of this process, which it will be repeated many times until meet this goal.

Table 4.1: The Procedures of the GA Technique

Stages	**Explanation**
Stage 1: Initiate the inhabitants	• Applying IEEE9 and IEC MG models and calculating the short circuits. • Early possible profiles of the OCRs operation time (1000 profiles).
Stage 2: Population assessment	• For each solution, the prime assess can be occurred via solving the optimum OF, Equation. (3.3). under bounds, from Equation. (3.4) to (3.7).
Stage 3: Selecting	• The most excellent two OCR OT profiles will be selected as parent.
Stage 4: Crossing	• For the following generation, a child profile will be launched, where will keep the popular genes while the rest of them will be chosen from the parent's profile at random. • The child profile must be a solution within the bounds of possibility.
Stage 5: Mutating	• In each iteration, a single gene occurred to update the child profile randomly. In this study, the setting of mutation is 0.1
Step 6: The model output and optimal solution	• Reaching the maximum number of iteration (200 iteration) by repeating the stages that have mentioned above, started with stage 2.

- *A Hybrid algorithm Gravitational Search Algorithm-Sequential Quadratic Programming (GSA-SQP):*

The GSA-SQP algorithm presented by (Radosavljević & Jevtić, 2016)-(Prashant Prabhakar Bedekar & Bhide, 2010) as powerful optimization solver for OCRs coordination. Firstly, as a multipoint method of search that is based on probability through using Gravitational Search Algorithm (GSA). Secondly, Non-Linear Programming (NLP) techniques such as Sequential

Quadratic Programming (SQP), which are single-point method of search, have the disadvantage of getting trapped in a local optimum point when the first option is closer to the local optimum. The NLP techniques offer a globally optimal solution if the correct first choice is made (Prashant Prabhakar Bedekar & Bhide, 2010). The study by (Prashant Prabhakar Bedekar & Bhide, 2010) suggested a hybrid of GSA with SQP to take advantage of the methods while overcoming their drawbacks. The SQP routine is introduced in GSA as a local technique of search to boost the convergence. Initially, the GSA method is performed the best fitness for each generation is chosen in each interaction. From this, the corresponding agent is set as the initial value of the variables in the SQPP technique. The SQP routine is then executed according to the local search's adopted the probability of local search (α_{LS}), improving the best fitness gotten from GSA in the current interaction. This is how the algorithm of GSA-SQP offers the global optimal solution. For calculating the optimal setting of the OCRs, several agents that represent a complete solution set is presented as the control variable of the OCRs coordination problem, X.

$$X = [TMS_j^1, \ldots., TMS_j^m, Ip_j^1, \ldots., Ip_j^m, A_j^1, \ldots., A_j^m] \tag{4.9}$$

where N is the population size (agents in the system), *j=1, 2, …., N* and *m* is the relays number in the grid. The process of the GSA-SQP started with a profile set of the first-generation OCRs operation time based on the power network and fault calculation data. Then, for each OCRs operation time profile, the objective function, Equation 4.4 is used as evaluating and fitness approach in this work. Thus, the best and worst solution will be selected. For the next generation, a random number will be generated and compared to the constant α_{LS}. In case of the random number less than the α_{LS}, the model will calculate the gravitational constant at time t, G(t) masses of agents, M(t) and the total force that acts on the *i*th agent at *t* time, F(t) to update velocity and position of searching agent. In case of the random number larger than the α_{LS}, the SQP method will be used to update the next generation by selecting the new agent as the best agent. Finally, the GSA-SQP model will finally select the optimal solution among all solutions which is helped to achieve the "global solution as shown in Figure 4.5 (Radosavljević & Jevtić, 2016).

The parameters of the algorithm applied for the optimal coordination problem in this paper are constant G0 is the initial gravitational which is set to 100, constant α is a user specified which is adjusted to 20. Both of constants G0 and α control the GSA performance. *t* is the current iteration while t_{max} is the maximum iteration number which is set to 200, *N* is adjusted to 50; α_{LS} is 95. For miscoordination problem, the β has been used. Miscoordination decreases through increasing of β, however, the relay OTs are risen. Thus, for omitting the miscoordination, a fit β value should be selected. In addition, there are other parameters related to local search should be calculated throughout the process which are: G(t) is gravitational constant at time t, M(t) is masses of agents, F(t) is the total force that acts on the *i*th agent at *t* time and a(t) is the acceleration of the *i*th agent. For meshed networks case studies, the weighting factors are chosen as α_1 and α_2 which are set to 2 and 15, respectively. IEEE 9-bus system β is set to 500 and the IEEE 30-bus system is set to1000.

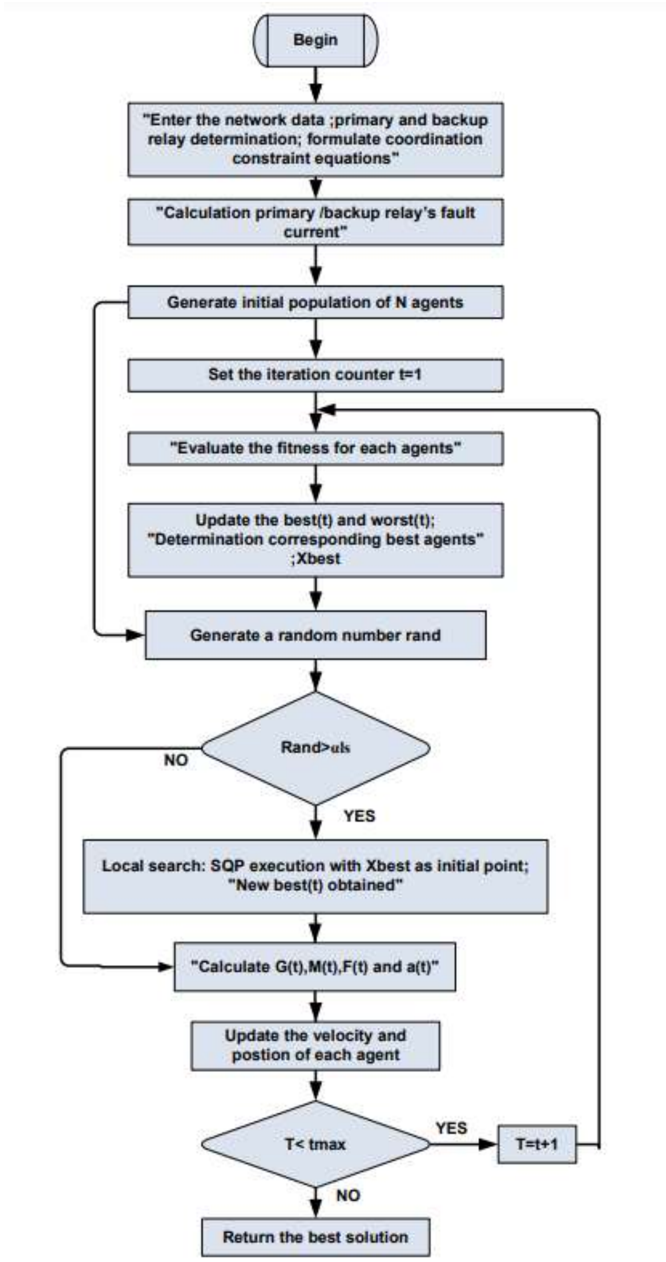


Figure 4.5: The flowchart of the GSA-SQP algorithm

4.4 *Simulation results and discussion*

This section aims to present the results of the proposed non-standard OCRs coordination approach, NSTCC, using radial and meshed distribution systems and under different operation scenarios. Throughout this section, the NSTCC will be compared to conventional OCR coordination scheme and non-standard OCR scheme developed by (Alasali et al., 2021). For solving the OCRs protection coordination problem, GA and hybrid GSA-SQP optimization techniques are used in this study. They are implemented in radial and meshed distribution systems under different operation modes based on the following network scenarios:

- Radial Networks: IEC MG benchmark and IEEE 9- bus test system
- Meshed Networks: IEEE 9 and IEEE 30- bus meshed networks

4.4.1 Radial Networks

In this part, an IEC MG benchmark and IEEE 9-bus test system have been carried out as a radial network. Afterwards, the short-circuit calculations in various modes and locations were achieved. In this. Figure 4.5 shows the flowchart of implementation the proposed NSTCC in both of abovementioned radial networks. Afterwards, the short circuit calculations in various modes and locations were achieved. In this section, the GA method has been us

ed to obtain the optimal setting (TMS and the coefficient A) for OCRs based on STCC (Alasali et al., 2021), NSS (Alasali et al., 2021) and the proposed NSTCC in the present thesis. Furthermore, the NSTCC has been compared with the STCC and NSS in term of reducing the relays' operation time, OT, and ensuring the CTI selectivity. For solving the OCRs protection coordination problem, GA technique is used in this section based on the abovementioned networks configurations in Figure 4.6.

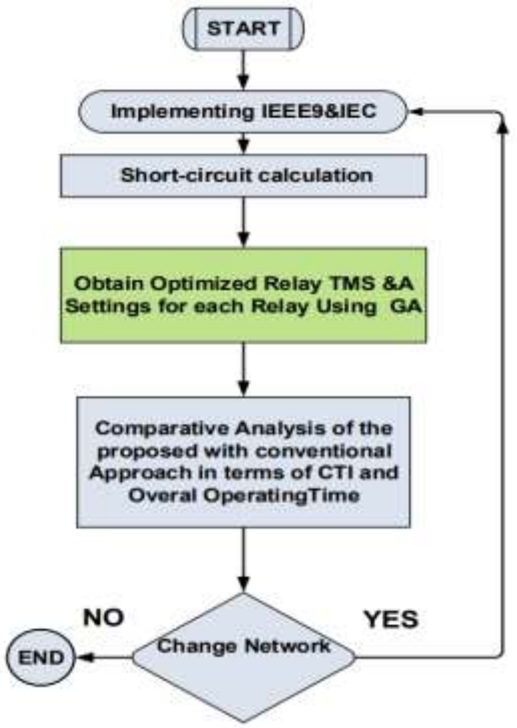


Figure 4.6: Flowchart of the Implementation the proposed NSTCC in Radial Networks

- *The Radial IEC MG Test System.*

IEC MG benchmark connected to various DG technology types has been used to evaluate the NSTCC of in this section. As shown in Figure 4.6 , it has four DGs (two wind turbines and two synchronous generators), five transformers and use 15 OCRs as well as five directional OCRs, DOCRs which are R1, R3, R5, R8 and R9, (Kennedy & Eberhart, 1995)-(Kar, 2017) give all details about IEC MG. The plug setting (PS) and current transformer ratio (CTR) for each OCR and DOCR are described as follows: for R1, R2, R3, R4, R5, R6, R8, R9, R10, R12, and R15, the PS and CTR are 0.5 and 400/1, respectively. Whereas for R11 and R14, the PS is 0.65 and CTR is the same as the previous OCRs, which is 400/1. The PS and CTR values of the R13 are 0.88 and 400/1. Finally, for R7, the PS and CTR are 1 and 1200/1, respectively (Alasali et al., 2021). A short circuit on different lines was calculated for each mode in this study. The three-phase faults at different transmission lines in the MG are illustrated in Figure 4.7. In Figure 4.7, the DG is considered as a permanent magnet synchronous generator (PMSG) system where the contribution of fault current is low, like our case with the PV system, compared to the DFIG system, which is considered as high fault: around 7 times the full load. However, the DFIG condition will be protected by the first relay after the generator in this work.

These fault cases are a fault on the line DL-5, named F1; a fault on the line DL-4, named F2; a fault on the line DL-2, named F3; a fault on the line DL-3, named F4; and a fault on the line

DL-1, named F5. To optimize the TMS for the coordination of OCRs, GA optimization processes have been carried out to test the NSTCC using MATLAB simulations. For fault conditions, the primary OCR should isolate the fault firstly. If it fails to trip the fault, after allowable CTI, the backup OCR must be operated; it is assumed to be operated between 0.2 s and 0.5 s. Three operational modes have been implemented in this IEC MG, as follows:

- Mode 1: the utility source is only connected to the IEC MG.
- Mode 2: the utility source and DGs are connected to the IEC MG.
- Mode 3: islanding mode, the DGs only connected to the IEC MG.

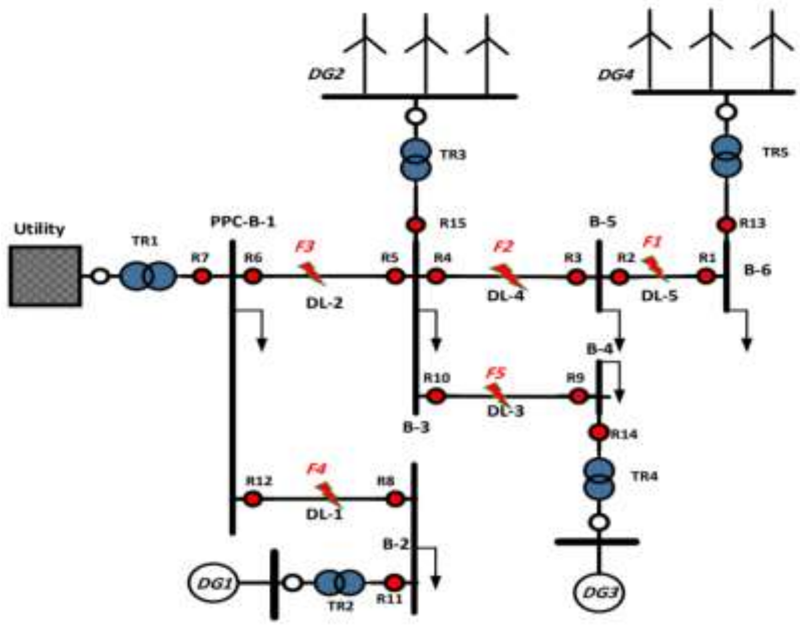


Figure 4.7: IEC MG Benchmark (Large Scale Network).

4.4.2 Simulation Results for Radial Networks

- The redial IEC MG Simulation Results in Mode 1

In this case, the main source is only connected to the IEC MG; however, all the DGs are off. For comparative purposes, the results of the TMS and the operating times for all relays that were obtained from the literature (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga, López-Lezama, & Muñoz-Galeano, 2021b)-(Sergio D Saldarriaga-Zuluaga, Jesús M López-Lezama, & Nicolás Muñoz-Galeano, 2020) and presented in Table 4.2. The authors in (Alasali et al., 2021) did not evaluate the IEC MG as redial system. It can be noticed that the proposed obtained OT equals 2.42s for the proposed NSTCC, which is a considerable reduction from those reported in Table 4.2.

Table 4.2: The Overall OT for the redial IEC MG - Mode 1

	(El-Naily et al., 2019)	(Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)	(Saldarriaga-Zuluaga et al., 2021b)	(Sergio D Saldarriaga-Zuluaga et al., 2020)	NSTCC	
Relay	TMS	TMS	TMS	TMS	Coefficient A	TMS Proposed
R1	-	-	-	-	-	-
R2	0.128	0.0500	0.05	0.0500	4.800	0.0501
R3	-	-	-	-	-	-
R4	0.259	0.1787	4.58	0.2306	4.800	0.3977
R5	-	-	-	-	-	-
R6	0.402	0.3223	2.16	0.7715	4.886	0.9223
R7	0.290	0.2060	0.05	0.055	4.826	0.1117
R8	-	-	-	-	-	-
R9	-	-	-	-	-	-
R10	0.128	0.0500	0.05	0.0500	4.801	0.0500
R11	-	-	-	-	-	-
R12	0.010	0.0500	0.05	0.0500	4.800	0.0504
R13	-	-	-	-	-	-
R14	-	-	-	-	-	-
R15	-	-	-	-	-	-
OT(s)	6.64	4.99	4.4	4.19	-	2.42

- The redial IEC MG Simulation Results in Mode 2

In this operational mode, the MG is connected to the main grid and the DG units. The results of the TMS and the operating times for all relays that were obtained from the literature (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga et al., 2021b)-(Sergio D Saldarriaga-Zuluaga et al., 2020) are presented in Table 4.3. It can be guaranteed that the value of the coordination between the primary and backup relays is achieved by obtaining the lowest tripping time for the NSTCC among the approaches reported in Table 4.3. The total OT was equal to 4.69 s for NSTCC compared to 11.6 s as the lowest OT value obtained from literature, which equals a 60% reduction for using NSTCC. Coefficient A's optimized value equals approximately 4.8 too according to the maximum fault current in this mode.

Table 4.3: The Overall OT for the redial IEC MG - Mode 2

	(El-Naily et al., 2019)	(Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)	(Saldarriaga-Zuluaga et al., 2021b)	(Sergio D Saldarriaga-Zuluaga et al., 2020)	NSTCC	
Relay	TMS	TMS	TMS	TMS	Coefficient A	TMS
R1	0.174	0.137	0.217	0.3893	4.801	0.188
R2	0.139	0,050	0.050	0.050	4.800	0.251
R3	0.087	0.050	0.050	0.050	4.801	0.050
R4	0.278	0.189	0.235	0.421	4.801	0.066
R5	0.172	0.115	0.197	0.394	4.801	0.050
R6	0.401	0.320	1.550	0.819	4.853	3.000
R7	0.284	0.244	0.050	0.273	4.820	0.103
R8	0.223	0.191	0.567	0.606	4.801	0.050
R9	0.069	0.050	0.050	0.050	4.808	0.050
R10	0.141	0.050	0.050	0.050	4.801	0.050
R11	0.244	0.218	0.470	0.452	4.802	0.144
R12	0.150	0.050	0.050	0.050	4.840	0.050
R13	0.194	0.167	0.325	0.746	4.800	0.245
R14	0.116	0.100	0.104	0.172	4.801	0.145
R15	0.170	0.136	0.280	0.297	4.801	0.115
OT(s)	17.48	13.66	11.6	12.48	-	4.69

- The redial IEC MG Simulation Results in Mode 3

In mode 3, the MG operates in islanding mode, which the main grid in off- grid mode and the load is supplied by all the DG units. The results of the OCRs coordination obtained from the literature (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga et al., 2021b)-(Sergio D Saldarriaga-Zuluaga et al., 2020) are shown in Table 4.4. In this case, too, the proposed approach NSTCC outperformed the other approaches that are reported in Table 4.4. The proposed NSTCC achieved an OT equal to 4.055 s as the lowest value among others in Table 4.4. Consequently, the coordination problems may not exist, which means the selectivity is guaranteed. The optimized value of coefficient A has been chosen as 6 in this mode to obtain the lowest OT value in Table 4.4.

Table 4.4: The Overall OT for the redial IEC MG - Mode 3

	(El-Naily et al., 2019)	(Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)	(Saldarriaga-Zuluaga et al., 2021b)	(Sergio D Saldarriaga-Zuluaga et al., 2020)	NSTCC	
Relay	TMS	TMS	TMS	TMS	Coefficient A	TMS
R1	0.173	0.137	0.548	0.389	6.000	0.154
R2	0.105	0.050	0.050	0.050	6.000	0.050
R3	0.086	0.050	0.050	0.050	6.000	0.050
R4	0.211	0.157	0.938	0.529	6.000	0.365
R5	0.209	0.155	0.862	0.862	6.000	3.000
R6	0.181	0.151	0.685	0.243	6.000	3.000
R7	-	-	-	-	-	-
R8	0.248	0.218	0.519	0.499	6.000	0.376
R9	0.069	0.050	0.050	0.050	6.000	0.050
R10	0.112	0.050	0.050	0.050	6.000	0.050
R11	0.265	0.240	0.490	0.431	6.000	0.415
R12	0.105	0.050	0.050	0.050	6.000	0.050
R13	0.193	0.167	0.778	0.100	6.000	0.200
R14	0.116	0.099	0.372	0.104	6.000	0.117
R15	0.177	0.148	0.670	0.630	6.000	1.827
OT(s)	15.56	12.63	9.99	8.96	-	4.055

4.4.3 Simulation Results for Radial 9-Bus Test Systems

The proposed network systems is developed based on the Canadian Urban Benchmark 4-bus feeder distribution system (Kennedy & Eberhart, 1995). As it shown in Figure 4.8, the IEEE 9 bus consists of one DG and 10 OCRs as well as 2 directional OCRs, DOCRs, which are R8 and R10. A utility main source feeds this radial distribution capacity of short-circuit = 500 MVA as well as ratio of X/R = 6 and all lines length = 500 m. The system is associated with the utility throughout a transformer of 20 MVA, 115kV / 12.47 KV. The simplified network, as shown in Figure 4.8, presents the OCRs and DOCRs, the PS and Current CTR for each OCR are stated as follows: for R1 and R5, the PS and CTR are 1.128 and 100/1, respectively, while 1.130 and 200/1 are the values of the PS and CTR for the R2 and R6. For all R3, R7, R8, and R9, the values of PS and CTR are 1.132 and 300/1, respectively. 1.135 and 400/1 are the PS and CTR values for all R4, R10, and R11. Lastly, the PS and CTR of the R12 are 1.140 and 600/1, respectively (Alasali et al., 2021). In the following subsection, the results of the proposed NSTCC, STCC, and NSS schemes are presented over different fault and power network model modes, as discussed in the previous section.

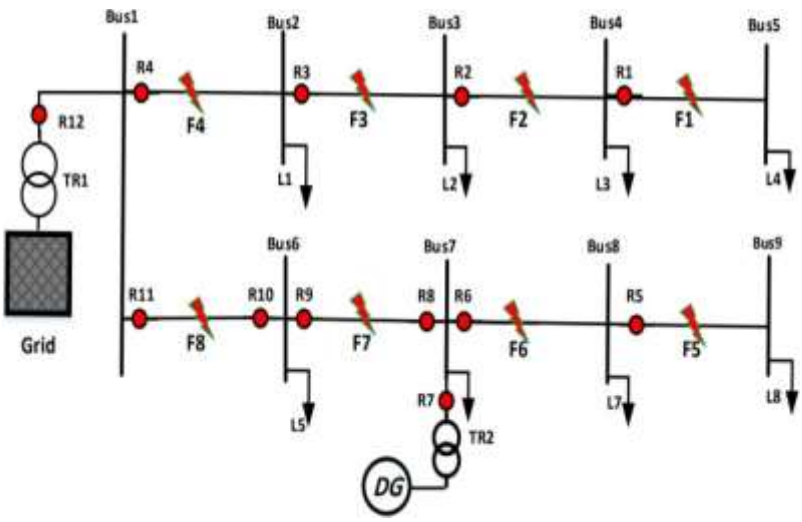


Figure 4.8: The IEEE 9 bus MG system

- IEEE 9-Bus Radial without DGs: Mode 1 test results

This mode represents a conventional power network, which is fed only via the main utility feeder without DGs, as shown in Figure 4.8. The GA optimization technique is used to evaluate the performance of the NTSCC method and compare it with the conventional STCC and the NSS (Alasali et al., 2021). In general, the optimized values of TMS, the overall OT and coefficient A in mode 1 for all OCRs are presented in Table 4.5. The acquired settings and the total tripping time were computed by utilizing MATLAB software and GA methodology. As shown in Table 4.5, the NSTCC approach is achieved the minimum overall OT of all OCRs which is equals 8.224s compared to STCC and NSS method which are equals 9.352 and 8.848s, respectively. In addition, the optimized value of coefficient A for the NSTCC approach has been chosen as approximately 5 for all OCRs as shown in Table 4.5, which is a suitable value for maximum current faults in this conventional power network case.

Table 4.5: The Overall OT for STCC, NSS and NSTCC Curves in IEEE 9-Bus Radial without DGs- Mode 1

Relays	STCC (Alasali et al., 2021) TMS	NSS (Alasali et al., 2021) TMS	NSTCC TMS	NSTCC A
R1	0.010	0.010	0.010	5.003
R2	0.139	0.171	0.300	5.000
R3	0.239	0.264	0.395	5.002
R4	0.322	0.345	0.486	5.000
R5	0.010	0.010	0.010	5.001
R6	0.139	0.171	0.300	5.000
R7	0.235	0.264	0.396	5.000
R8	0.319	0.345	0.479	5.017
R9	0.367	0.384	0.501	5.000
R10	-	-	-	-
R11	-	-	-	-
R12	-	-	-	-
OT(s)	9.352	8.848	8.224	

- IEEE 9-Bus Radial with DGs: Mode 2 test results

This mode tests and evaluates the NSTCC on the network that is fed by all types of DGs, as illustrated in Figure 4.8. Table 4.6 shows the optimized values of TMS, the overall OT, and coefficient A in mode 2 for all OCRs. The total OT of the NSTCC in mode 2 of all OCRs equals 9.327 s, while the overall OTs for the STCC and NSS are 11.282 and 10.353 s, respectively. As with mode 1, an appropriate optimized value of coefficient A has been selected in mode 2 for the NSTCC approach, which is approximately 5 for all OCRs as illustrated in Table 4.6. As a result, the NSTCC scheme has recorded the lowest overall OT in Table 4.6 and optimal optimized value of the coefficient A.

Table 4.6: The Overall OT for STCC, NSS and NSTCC Curves in IEEE 9-Bus Radial Mode 2

Relays	STCC (Alasali et al., 2021) TMS	NSS (Alasali et al., 2021) TMS	NSTCC	
			TMS	A
R1	0.010	0.010	0.010	5.001
R2	0.139	0.171	0.276	5.084
R3	0.237	0.264	0.397	5.001
R4	0.321	0.345	0.437	5.001
R5	0.010	0.0100	0.010	5.001
R6	0.139	0.166	0.277	5.022
R7	0.062	0.161	0.177	5.004
R8	0.237	0.258	0.373	5.017
R9	0.010	0.010	0.010	5.003
R10	0.010	0.010	0.010	5.002
R11	0.118	0.132	0.191	5.001
R12	0.367	0.384	0.466	5.001
OT(s)	11.282	10.353	9.327	

- IEEE 9-Bus Radial under the islanding condition: Mode 3 test results

The grid's operational way in this mode is called islanding mode. Applying the NSTCC on the network with this mode shows the reliability and effectiveness of the proposed approach with a low fault current. Over the islanding mode, a comparison has been made between the proposed approach and other approaches in the Table 4.7, in terms of the optimized values of TMS and the overall OT. Similarly, the NSTCC approach achieves the minimum overall operational time of all OCRs compared to STCC and NSS approaches. The overall OT of all OCRs in mode 3 is 1.3728, 1.34, and 1.187 s for STCC, NSS, and NSTCC, respectively. It can be noticed that the optimized value of coefficient A in the Table 4.7 (islanding mode) for the NSTCC approach has been chosen to be approximately 2, which is suitable for detecting the minimum fault currents, and it is considered the key contribution of this NSTCC approach without delaying time during the optimization task.

Table 4.7: The Overall OT for STCC, NSS and NSTCC Curves in IEEE 9-Bus Radial Mode 3

Relays	STCC (Alasali et al., 2021) TMS	NSS (Alasali et al., 2021) TMS	NSTCC TMS	NSTCC A
R1	-	-	-	-
R2	-	-	-	-
R3	-	-	-	-
R4	-	-	-	-
R5	0.010	0.010	0.010	2.000
R6	0.039	0.077	0.291	2.050
R7	0.137	0.129	0.438	2.049
R8	-	-	-	-
R9	-	-	-	-
R10	-	-	-	-
R11	-	-	-	-
R12	-	-	-	-
OT(s)	1.373	1.34	1.187	

4.4.4 Simulation Results for Meshed Networks

In this section, IEEE 9- and 30-bus meshed networks have been implemented to evaluate the proposed NSTCC approach. Figure 4.9 shows the flowchart for the implementation of NSTCC in meshed networks. Afterwards, the short-circuit calculations in various modes and locations were performed. The MATLAB software is used to implement the proposed equation with the constant coefficient 5.8 and with the variable coefficient A for obtaining the short-circuit calculations. The optimal setting, TMS, the coefficient A, and Ip for OCRs have been obtained by using the MATLAB software and applying the hybrid GSA–SQP algorithm for the NSTCC approach. Finally, the NSTCC with a constant coefficient 5.8 and a variable constant A has been compared with the STCC to show the effectiveness of the proposed approach in terms of reducing the OT considerably and ensuring the CTI selectivity. The main steps of using the hybrid GSA–SQP by applying it in the MATLAB software can be shown as follows:

- The objective function for the IEEE 9-bus system is run on the MATLAB software; it includes the short-circuit calculation values for all points that have been illustrated in Figure 4.8 from point A to L.
- For example, when the fault occurs at point A: for primary R1, backup R15, and R17, the fault current was 24779 A, 9150 A, and 15632 A, respectively. The OT of primary and backup relays for faults in A have been calculated based on Equation 4.2. The best value of the A parameter in Equation 4.2 will be determined by solving the cost function in Equation 4.4 by using GSA–SQP in the MATLAB platform.

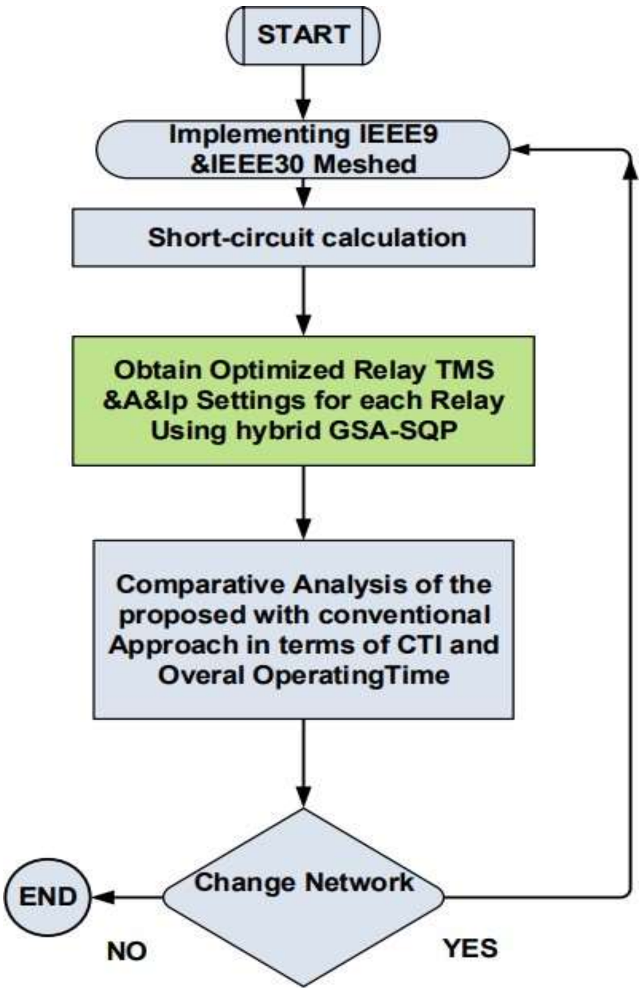


Figure 4.9: Meshed Networks Flowchart of the Proposed NSTCC

- *Description of the Meshed 9-Bus Test Systems Under Study*

For solving the OCR coordination problem, the NSTCC is applied to this 9-bus test system by using the hybrid GSA–SQP algorithm. This grid consists of 12 lines and 24 OCRs, and every line has two relays at both ends as illustrated in Figure 4.10. The power is received via bus 1, which is represented by a source of 100 MVA, 33 KV and more details about this grid are given in (Prashant Prabhakar Bedekar & Bhide, 2010). Twelve fault points have been considered, indicated from A to L (one on each line) as shown in the Figure 4.10. For these fault points, Table 4.8 shows the primary-backup relationship of relays and the CTI is taken at minimum 0.2s. In case of fault at different points, the short circuit analysis has been conducted to find the current seen by the relays.

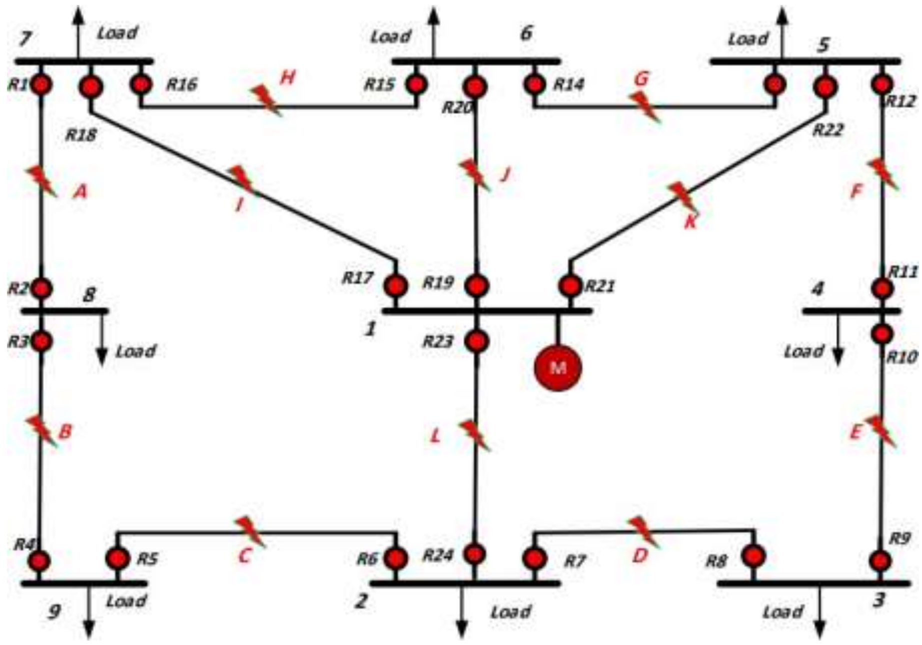


Figure 4.10: IEEE 9-Bus MG system, meshed network

Table 4.8: CTI for the Meshed 9-bus Test System

Backup Relay	Primary Relay	CTI (s)	Backup Relay	Primary Relay	CTI (s)
R15	R1	0.200	R11	R13	0.200
R17	R1	0.218	R21	R13	0.200
R4	R2	0.200	R16	R14	0.200
R1	R3	0.200	R19	R14	0.200
R6	R4	0.200	R13	R15	0.200
R3	R5	0.200	R19	R15	0.201
R8	R6	0.200	R2	R16	0.200
R23	R6	0.203	R17	R16	0.200
R5	R7	0.200	R2	R18	0.309
R23	R7	0.200	R15	R18	0.317
R10	R8	0.200	R13	R20	0.322
R7	R9	0.200	R16	R20	0.322
R12	R10	0.200	R11	R22	0.309
R9	R11	0.200	R14	R22	0.320
R14	R12	0.203	R5	R24	0.318
R21	R12	0.235	R8	R24	0.315

The optimized TMS and Ip values and OTs based on a hybrid GSA–SQP algorithm are compared with obtained results in ref (Radosavljević & Jevtić, 2016). The NSTCC reduces the overall operational time of primary OCRs to 1.869s compared to the results that are illustrated in Table 4.9. The coefficient A's optimized value is selected to be approximately 6.25 by MATLAB software operations in this case to obtain the lowest OT. The corresponding values of CTI are shown in the Table 4.8. The optimum results ensure the coordination between primary and backup relays. Further, the CTI is improved by using the NSTCC approach; the sum of CTI values equals 7.392, which is reduced compared with the sum of CTI values in ref (Radosavljević & Jevtić, 2016), which equals 8.892. The NSTCC scheme results in the best settings.

Table 4.9: Optimal TMS, Ip and A for the Meshed 9-bus Test System

Relay	STCC (Radosavljević & Jevtić, 2016)			NSTCC with Constant Coefficient A				NSTCC			
	TMS	Ip	OT_{primary}	TMS	A	Ip	OT_{primary}	TMS	A	Ip	OT_{primary}
R1	0.276	2.500	0.629	0.680	5.800	0.500	0.201	0.645	6.250	0.500	0.029
R2	0.091	2.500	0.332	0.107	5.800	0.500	0.157	0.102	6.250	0.500	0.155
R3	0.197	2.500	0.524	0.264	5.800	0.500	0.146	0.267	6.250	0.500	0.161
R4	0147	2.500	0.408	0.243	5.800	0.500	0.171	0.234	6.250	0.500	0.176
R5	0.139	2.500	0.470	0.110	5.800	0.500	0.143	0.118	6.250	0.500	0.159
R6	0.219	2.500	0.509	0.528	5.800	0.500	0.042	0.500	6.250	0.050	0.646
R7	0.221	2.500	0.515	0.553	5.800	0.500	0.044	0.521	6.250	0.050	0.674
R8	0.138	2.500	0.467	0.109	5.800	0.500	0.141	0.117	6.250	0.050	0.157
R9	0.148	2.500	0.402	0.244	5.800	0.500	0.157	0.234	6.250	0.500	0.163
R10	0.312	3.525	0.912	0.263	5.800	0.500	0.143	0.265	6.250	0.500	0.158
R11	0.148	2.500	0.402	0.107	5.800	0.500	0.157	0.102	6.250	0.500	0.155
R12	0.197	2.500	0.766	0.630	5.800	0.500	0.186	0.602	6.250	0.500	0.027
R13	0.092	2.500	0.334	0.175	5.800	0.500	0.101	0.145	6.250	0.500	0.091
R14	0.272	2.500	0.619	0.288	5.800	0.500	0.118	0.166	6.250	0.500	0.076
R15	0.190	2.500	0.508	0.299	5.800	0.500	0.123	0.165	6.250	0.500	0.075
R16	0.189	2.500	0.508	0.172	5.800	0.500	0.100	0.146	6.301	0.500	0.092

R17	0.500	0.542	-	0.287	5.800	0.890	0.000	0.179	6.250	0.813	0
R18	0.072	1.979	0.232	0.034	5.800	1.553	0.103	0.010	6.364	0.500	0.015
R19	0.315	1.693	-	0.302	5.800	0.537	0.000	0.130	6.250	1.035	0
R20	0.064	2.201	0.205	0.017	5.800	0.785	0.033	0.010	6.250	0.500	0.014
R21	0.482	0.597	-	0.188	5.800	1.445	0.000	0.116	6.250	1.632	0
R22	0.092	1.902	0.229	0.049	5.800	0.668	0.093	0.010	6.250	0.500	0.015
R23	0.424	0.682	-	0.214	5.800	0.871	0.000	0.222	6.354	0.817	0
R24	0.101	0.964	0.271	0.010	5.800	0.500	0.019	0.010	6.250	0.500	0.019
OT(s)	8.892			2.377				1.870			

- *Description of the Meshed 30-Bus Test Systems Under Study*

The IEEE 30-bus system is considered as a meshed test system in this study to evaluate the proposed approach efficiency in solving large, meshed networks. As shown in Figure 4.11, it has 19 lines and 38 DOCRs and it receives the power from three distribution substations by bus 1, 6 and 13, each one is represented by a source of 132MVA, 33KV as well as with two DG units. The fault points are nineteen demonstrated as L1 to L19, for each line one fault point as shown in Figure 4.11. The primary-backup coordination of relays for those fault points and CTI values are illustrated in Table. 4.10.The configurations of the short circuits current values and more information can be existed in (Christie, 1993). The TMS range is between 1.1 to 1 and for Ip from 1.4 to 5.9. The minimum value of the CTI is set as 0.3s.

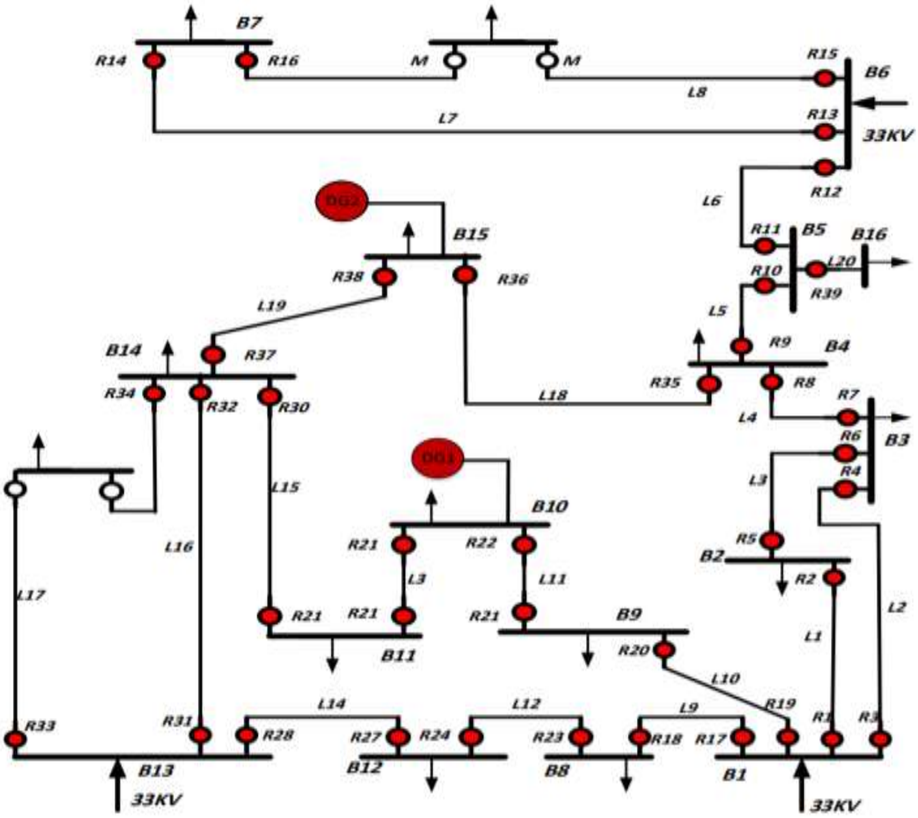


Figure 4.11: IEEE 30-Bus MG system (Large Scale Network

Table 4.10: CTI for the Meshed 30-bus Test System

Backup relay	Primary Relay	CTI (s)	Backup Relay	Primary relay	CTI (s)	Backup relay	Primary Relay	CTI (s)
R1	R3	0.300	R15	R19	0.300	R25	R24	0.300
R2	R4	0.514	R15	R36	0.463	R28	R1	0.301
R2	R22	0.300	R16	R19	0.310	R28	R2	0.413
R3	R4	0.300	R16	R34	0.301	R28	R10	0.300
R3	R21	0.436	R16	R36	0.488	R29	R1	0.319
R4	R5	0.300	R17	R19	0.301	R29	R2	0.431
R4	R18	0.305	R17	R34	0.305	R29	R9	0.301
R5	R6	0.300	R17	R35	0.349	R30	R29	0.300
R6	R7	0.331	R18	R38	0.300	R31	R28	0.300
R6	R8	0.300	R19	R37	0.301	R32	R30	0.300
R7	R27	0.302	R20	R2	0.443	R33	R31	0.300
R8	R26	0.300	R20	R9	0.300	R34	R32	0.300
R9	R12	0.300	R20	R10	0.317	R35	R17	0.606
R10	R11	0.300	R21	R1	0.327	R35	R33	0.317
R11	R13	0.300	R21	R9	0.301	R36	R16	0.507
R12	R14	0.300	R21	R10	0.317	R36	R33	0.302
R13	R15	0.300	R22	R20	0.300	R37	R5	0.453
R14	R16	0.301	R23	R21	0.647	R37	R23	0.300
R14	R17	0.378	R23	R22	0.300	R38	R34	0.302
R15	R19	0.300	R24	R18	0.458	R38	R35	0.342
R15	R35	0.332	R24	R23	0.300	R38	R36	0.474

The optimized values of TMS, Ip, and OTs utilizing NSTCC with the hybrid GSA–SQP algorithm are illustrated in Table 4.11. It can be noticed from these results that NSTCC is the best approach and achieved the minimum overall OT of all OCRs of 12.231s compared to 26.826 s and 19.727 s, for the STCC and NSS, respectively, as is shown in Table 4.11. The CTI values calculated from the optimized TMS and Ip are shown in Table 4.10 and the coordination between primary and backup relays are ensured by the optimal results. Therefore, this signifies that the NSTCC can be efficiently used for solving the OCR coordination problem for the meshed and large-scale power systems.

Table 4.11: Optimal TMS, Ip and A for the Meshed 30-bus Test System

Relay	STCC (Radosavljević & Jevtić, 2016)			NSS				NSTCC			
	TMS	Ip	$OT_{primary}$	TMS	A	Ip	$OT_{primary}$	TMS	A	Ip	$OT_{primary}$
R1	0.304	3.816	0.901	0.647	5.8	1.595	0.458	0.550	4.301	2.294	0.274
R2	0.346	1.500	0.713	0.322	5.8	2.207	0.352	0.331	4.185	2.594	0.164
R3	0.276	2.756	0.946	0.395	5.8	1.895	0.707	0.323	4.199	2.501	0.441
R4	0.258	2.693	0.766	0.424	5.8	1.669	0.525	0.477	4.089	1.892	0.237
R5	0.263	1.659	0.661	0.317	5.8	1.690	0.436	0.293	4.212	2.438	0.317
R6	0.160	1.981	0.607	0.180	5.8	1.831	0.443	0.176	4.123	2.028	0.301
R7	0.173	1.824	0.430	0.203	5.8	1.529	0.215	0.258	4.024	1.620	0.041
R8	0.157	1.587	0.372	0.190	5.8	1.500	0.199	0.227	4.121	1.689	0.074
R9	0.313	3.353	0.901	0.622	5.8	1.656	0.523	0.535	4.131	2.537	0.293
R10	0.312	3.525	0.912	0.713	5.8	1.500	0.487	0.746	4.188	2.174	0.278
R11	0.280	2.784	1.053	0.910	5.8	2.214	0.910	0.410	4.388	2.538	0.736
R12	0.217	3.594	0.765	0.440	5.8	1.500	0.525	0.39	4.099	1.946	0.252
R13	0.249	2.618	0.872	0.431	5.8	1.525	0.712	0.373	4.141	2.523	0.538
R14	0.216	2.140	0.772	0.285	5.8	1.500	0.550	0.188	4.181	1.706	0.243
R15	0.233	1.606	0.757	0.298	5.8	1.500	0.612	0.283	4.116	1.836	0.408
R16	0.268	3.071	0.793	0.507	5.8	1.500	0.463	0.593	4.089	1.660	0.083
R17	0.147	1.629	0.318	0.246	5.8	1.620	0.187	0.207	4.058	1.924	0.010
R18	0.241	2.493	0.735	0.439	5.8	1.500	0.562	0.416	4.119	1.946	0.312
R19	0.241	2.839	0.728	0.447	5.8	1.627	0.535	0.468	4.116	2.142	0.320

R20	0.144	2.398	0.499	0.254	5.8	1.500	0.430	0.217	4.143	1.943	0.256
R21	0.160	1.500	0.377	0.201	5.8	1.855	0.277	0.179	4.194	1.874	0.106
R22	0.170	4.008	0.694	0.358	5.8	1.945	0.624	0.363	4.144	2.518	0.449
R23	0.210	2.568	0.731	0.401	5.8	1.500	0.646	0.405	4.092	2.096	0.468
R24	0.202	2.236	0.772	0.302	5.8	2.158	0.764	0.346	4.084	2.168	0.596
R25	0.252	2.663	-	0.365	5.8	2.885	0.000	0.329	4.599	3.105	0.000
R26	0.111	1.510	0.625	0.100	5.8	1.500	0.334	0.116	4.089	1.623	0.293
R27	0.122	1.636	0.557	0.100	5.8	1.500	0.285	0.107	4.021	1.597	0.210
R28	0.193	2.549	0.963	0.259	5.8	1.808	0.690	0.235	4.174	2.157	0.572
R29	0.164	2.673	0.731	0.280	5.8	1.500	0.597	0.269	4.064	1.742	0.375
R30	0.184	3.672	0.901	0.378	5.8	1.797	0.808	0.366	4.101	2.371	0.589
R31	0.219	3.069	0.903	0.401	5.8	1.559	0.734	0.390	4.119	2.159	0.541
R32	0.209	3.217	0.953	0.473	5.8	1.500	0.910	0.487	4.159	1.906	0.685
R33	0.286	3.177	0.843	0.582	5.8	1.500	0.582	0.604	4.092	2.209	0.285
R34	0.252	3.661	0.834	0.629	5.8	1.500	0.631	0.712	4.098	1.962	0.329
R35	0.229	2.453	0.729	0.301	5.8	1.718	0.301	0.312	4.072	2.089	0.302
R36	0.100	1.500	0.222	0.140	5.8	4.168	0.315	0.123	4.636	2.725	0.161
R37	0.214	2.355	0.703	0.385	5.8	1.500	0.606	0.408	4.084	1.930	0.408
R38	0.194	2.888	0.790	0.352	5.8	1.644	0.690	0.217	4.108	2.046	0.418
OT(s)	26.826			19.727				12.231			

4.5 Summary and discussion

This chapter represents a significant contribution to the field of power systems protection coordination. The non-standard time current characteristics of the algorithmic function presented in this chapter, when integrated with DGs, have been shown to significantly improve coordination under faulty conditions and varying modes. The following conclusions are drawn based on theoretical analysis and simulation verification:

- The proposed NSCCT coordination approach ensures that appropriate coordination is achieved with minimal operation time during line faults or power outages. Furthermore, the coordination of all OCRs is achieved without requiring any communication, making the proposed method highly practical and efficient.
- Additionally, the NSTCC protection coordination approach can effectively handle miscoordination caused by DGs accessing the system. This is a significant advantage over traditional coordination methods that may not account for such scenarios.
- It is important to note that the proposed NSTCC method has been rigorously compared to conventional coordination methods and non-standard characteristics reported in the literature. The results of the simulations clearly demonstrate the superior reliability and selectivity of the NSCCT method, making it a high performed alternative to traditional coordination methods. The following paragraphs proves this,

For IEC MG radial network, the performance of proposed NSTCC and approaches from the literature (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga et al., 2021b)-(Sergio D Saldarriaga-Zuluaga et al., 2020) on the redial IEC MG over the different operation modes is presented. The overall operation time, OT, for relays was obtained by using GA algorithm and shown in Figure 4.12. The results viewing that the NSTCC approach reduced the overall OT of OCRs for all modes compared to the literature (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga et al., 2021b)-(Sergio D Saldarriaga-Zuluaga et al., 2020) approaches. For example, compared to the literature approaches (Sergio Danilo Saldarriaga-Zuluaga et al., 2020b)-(El-Naily et al., 2019)-(Saldarriaga-Zuluaga et al., 2021b)-(Sergio D Saldarriaga-Zuluaga et al., 2020), the NSTCC significantly reduced the overall OT in Mode 1 by 63.55%, 55.5%, 45.0%, and 47.7%, respectively.

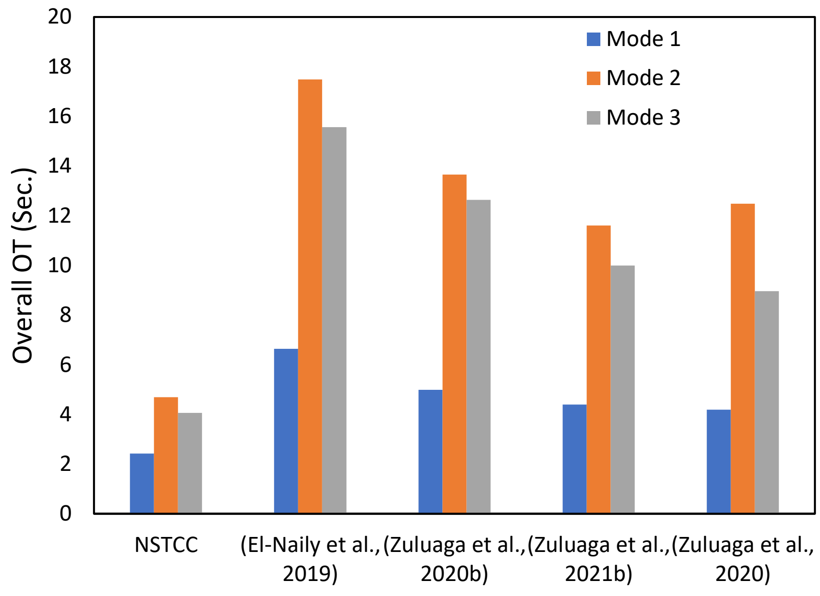


Figure 4.12: The overall OT in Modes 1, 2 and 3 for the radial IEC MG

The performance of the proposed NSTCC, NSS, and STCC approaches on the radial IEEE 9-bus system over the different operation modes is presented. The overall OT for operation modes shown in Figure 4.13 was obtained by using the GA algorithm. The outcomes above show that the NSTCC approach reduced the overall OT of OCRs for all modes compared to NSS and STCC approaches. For example, the NSTCC reduced the overall OT in Mode 2 by 17.32% and 9.91% compared to NSS and STCC approaches, respectively.

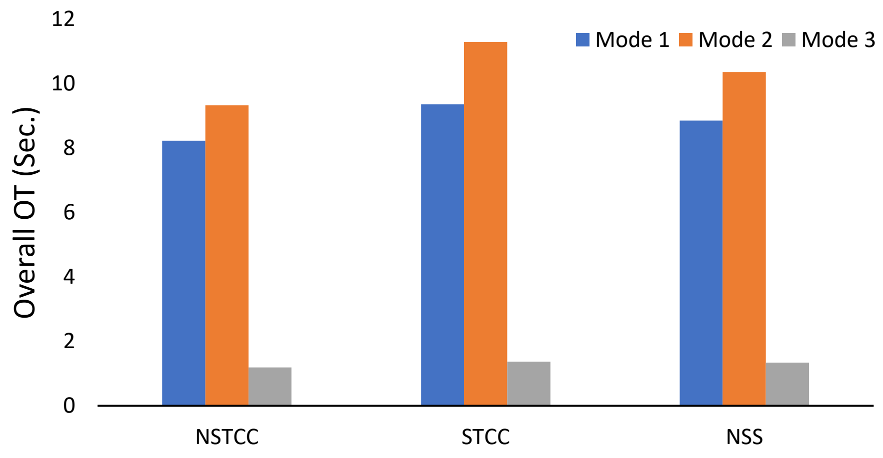


Figure 4.13: The overall OT in Modes 1, 2 and 3 for the radial IEEE 9-bus system

In this regard, the performance of the proposed NSTCC and approaches from the literature STCC and NSTCC with constant coefficient A on the IEEE 9- and 30-bus meshed networks are presented. The overall OTs for operation modes are shown in Figure 4.14 and were obtained by using the hybrid GSA–SQP algorithm. The results above illustrate that the NSTCC approach reduced the overall OT of OCRs for all modes dramatically compared to approaches from the literature. For example, the NSTCC reduced the overall OT in the meshed 30-bus test system by 54.4% and 37.9% compared to the literature approaches STCC and NSS, respectively.

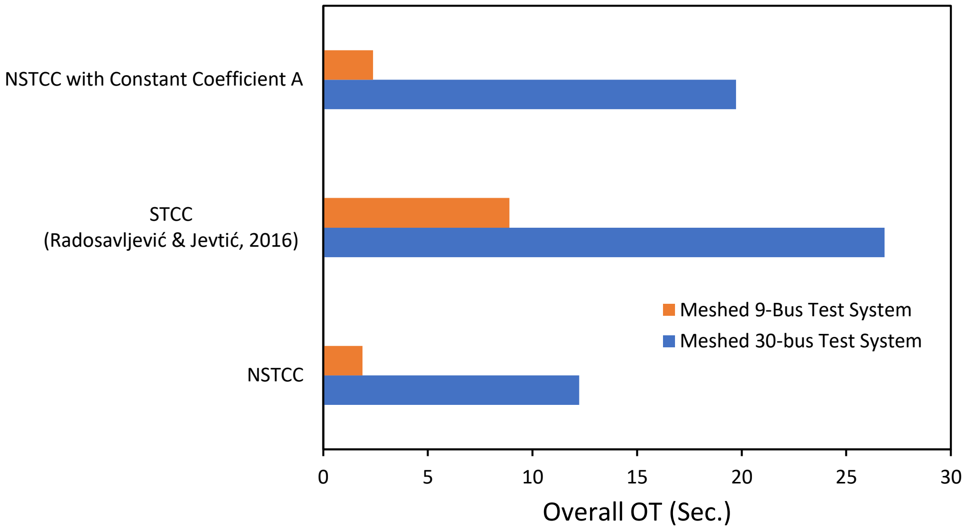


Figure 4.14: The overall OT in NSTCC with constant coefficient A, STCC and NSTCC for the meshed 9 and 30 MG

Overall, this chapter serves as a valuable resource for researchers and professionals in the field of power systems protection coordination. The proposed NSTCC method is a significant advancement that has the potential to significantly improve the reliability and efficiency of power systems.

Chapter 5: Optimizing Overcurrent Relay Coordination Scheme Based on A Hybrid Water Cycle Moth Flame Optimization (HWCMFO) Algorithm Considering IEC Normal Inverse Curve Limitations

5.1 Introduction

Developing and employing optimization algorithms is essential for resolving power protection issues in a power network with DG because these algorithms provide efficient and effective solutions to power protection's complex problems. Integration of DG units into power networks has created unique operational challenges, such as fault detection, identification, and localization, which necessitate the use of sophisticated techniques for dependable and efficient operation. Algorithms for optimization permit the selection of optimal settings for protective relays and the coordination of protective devices in power networks with DG. These algorithms can evaluate various protection schemes and identify the optimal solution that satisfies the sensitivity, selectivity, and speed requirements of the system. In addition, optimization algorithms can deal with the complex constraints and non-linearities of power protection systems in DG networks. These algorithms can consider various modes, such as load demand changes, faults, and the operation modes of DG units, and provide dependable and efficient solutions. Using optimization algorithms to solve power protection issues in DG networks can enhance the power system's dependability, stability, and safety. These algorithms can optimize the performance of protective devices and guarantee the prompt isolation of defects in order to minimize the impact on the power network. In addition, optimization algorithms can reduce the computational costs of power protection systems, resulting in cost savings and enhanced efficiency.

The goal of this chapter is to obtain reliable and optimal settings of OCRs and ensure selectivity between them with the presence of DGs in the DNs. In this chapter, a proposed method in (El-Naily et al., 2019) has been developed as a NSCs method, which improves the performance of the OCRs protection; it represents an alternative to the coordination of the conventional protection approach. A non-standard curve has been added that takes into consideration PSM adding to apply a new algorithm based on HWCMFO as an optimization technique method to present its impact in industrial relays to contribute towards solving the OCRs coordination problem in term of CTI between primary and backup relay pairs and overall operation time that to enhance the outcomes' reliability of this proposed approach. that. The contributions of this chapter have been highlighted as follows:

- Highlighting and investigation the issues built-in the nowadays in industrial relays encountered, when using the optimization techniques without taken into account the tripping characteristics.
- Implementing of the proposed HWCMFO algorithm in the industrial relays and comparing the results in term of tripping time and speed calculation with PSO as a heuristic technique to prove its reliability, stability and speed computer calculation compared to existence techniques.
- Proposing NSC approach in commercial OCRs via extending the IEC normal inverse curve to 50 PSM that for complying with the extreme faulty current conditions caused by a high penetration of intermittent DG.
- Producing comparatives between proposed NSC scheme results and the standard IEC normal inverse characteristics included-in existence industrial relays in the modern DNs based on the proposed hybrid technique.

Chapter 5 of this thesis introduces a novel optimization technique for minimizing the total tripping time of OCRs by determining the optimal relay settings at the power network with DGs under different fault scenarios. The main contribution of this chapter has been published in a paper titled "Optimal overcurrent relay coordination based on hybrid water cycle moth flame optimization (HWCMFO) algorithm considering standard and non-standard characteristics of microgrids" in the 16th International Conference on Developments in Power System Protection (DPSP 2022). This paper demonstrates the effectiveness of the HWCMFO algorithm in comparison to common and standard heuristic optimization, PSO technique. The proposed HWCMFO algorithm considers both standard and non-standard characteristics of MGs, and it can optimize OCR coordination schemes with high efficiency and accuracy. The main contribution in this paper is from S. Abeid as first author including conceptualization, methodology, investigation, software, validation, formal analysis, resources, visualization, writing—original draft preparation, writing—review and editing.

5.2 Problem Statement

Chapter 4 of this thesis is where the problem statement is outlined, and a novel non-standard curve is introduced to address the issue of OCRs coordination in DNs with DGs. However, this chapter goes above and beyond by presenting a new hybrid optimization technique, which is coupled with the new non-standard characteristic approach applying for solving industrial relays problems. The subsection that follows takes a deep discuss into this problem, specifically within built-in industrial OCRs. Overall, this chapter is interested in the latest advancements in OCRs coordination and optimization techniques. The new proposed hybrid optimization technique coupled with the non-standard characteristic approach promises to be powerful tool in the field of power systems protection coordination, and this chapter provides a comprehensive analysis of its efficacy.

5.2.1 Impacting of the high fault currents on standard IEC normal inverse characteristics.

In conventional relays, the responsiveness of the tripping characteristics of engineered OCRs is typically limited to a certain special potential of PSM. In times of major fault currents in contemporary DNs with large-share DGs, this restriction may worsen the responsiveness of time–current inverse features utilized in the OCRs. The tripping features of engineered OCRs are typically restricted to certain PSM values, usually 20 times PSM, which restrict the characteristics of the OCR scheme to maintain sufficient synchronization between different OCRs within the DN. The increased level of DGs in modern MV-DN increases the short-circuit level to an inappropriate value beyond the operating regions (1.1–20 PSM) of the usually inverse features built-in industrial OCRs. These increased amounts of current can trigger the current of fault to accumulate in the definite region and set the designated OCRs operating time to a fixed value. As a result, in instances of fault current above the PSM_{max} of OCRs in the DN, collaboration of over-current schemes may be impacted or even worsened.

The standards act in the upstream grid of primary and backup OCRs must meet certain conditions to lessen the impact of high fault currents on network output reliability. The tripping features built-in industrial OCRs offered by several producers typically range from PSM_{min} 1.1 PSM to PSM_{max} twenty times PSM (J. Das, 2017). The cooperation between the primary and backup relays can be preserved for fault conditions lower than PSM_{max} and the responsiveness of OCR is appropriately manipulated. Nevertheless, the responsiveness of the OCR scheme may not be attained for serious fault current in the grid exceeding 20 times of the PSM.

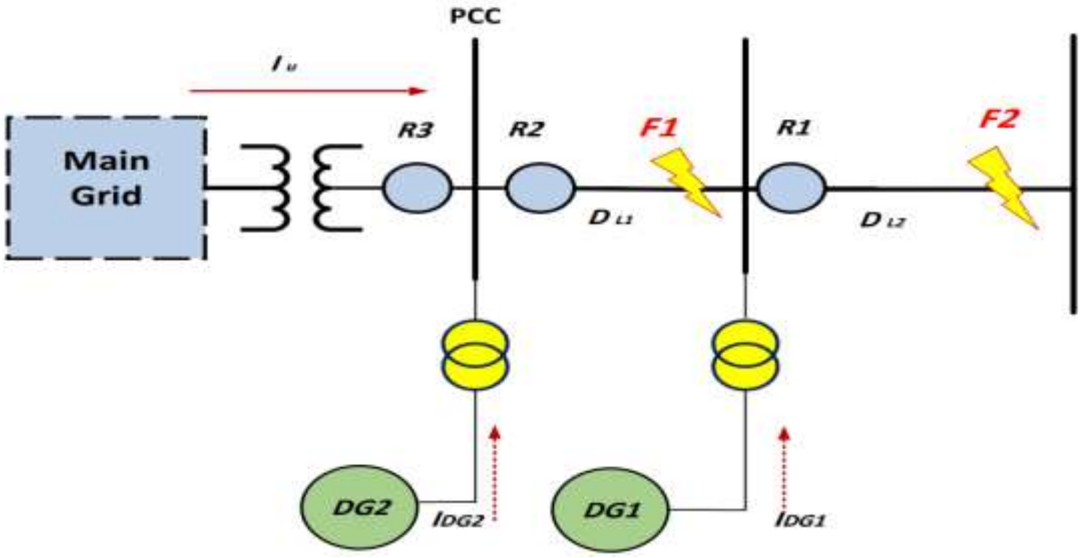


Figure 5.1: Traditional OCR coordination without DGs

The incidences of high fault currents exceeding the PSM max trigger the specific component of the circuit to trip the error. As a consequence, improper coordination between the main and replacement OCR pairs may be generated due to the decrease in CTI for all relays, and the risk of inconvenience and unnecessary tripping inside the network could be increased. Find the specified device in Figure 5.1 were linked without DGs. The calculated current through primary relay I_{p} (R_2) and backup relay I_b (R_3) can be interpreted as if a fault occurred downstream at (point F1).

$$I_{\text{p}} = I_b = I_{\text{U}} = \frac{Vs}{Zt} \tag{5.1}$$

where I_{p} is a primary relay, I_b is a backup relay, I_{U} is the fault contribution current from the utility grid, Vs is the voltage of the network and Zt is the total impedance between the upstream network and the fault location.

For primary and backup OCRs both I_{p} and I_b will be the same. When OCR is configured on one of the numerous feeders linked to the linkage transformer's secondaries, and if the OCR pick-up current configured on the transformer's secondaries has a different impact than the OCR pick-up current configured on one of the numerous feeders attached to that transformer, each OCR will see the same fault current as a different multiple PSM.

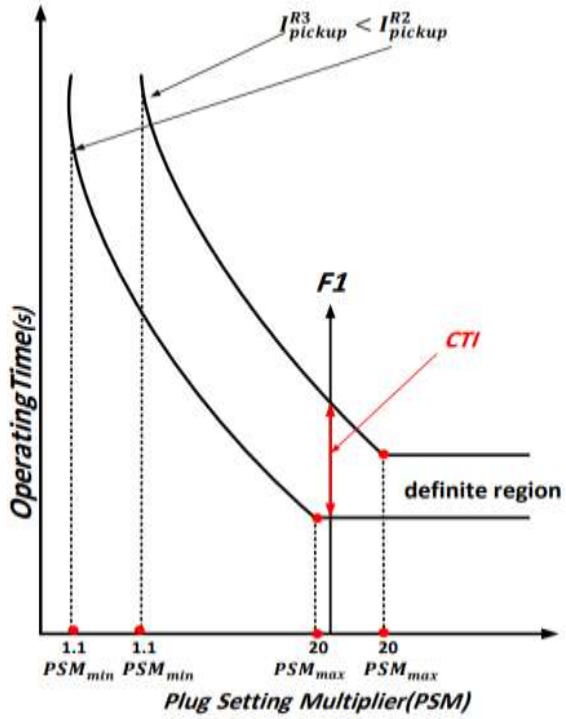


Figure 5.2: The primary and backup OCRs characteristics curves without DGs

From Figure 5.2 when the fault occurs at (point F1), the primary R_2 will insulate the fault firstly on the feeder as well as R_3 on the backups of the combined power transformer will backup R_2 and insulate the fault at point F1 in situation of R_2 be unsuccessful to insulate fault afterward acceptable CTI amount time. Where the PSM vary among R_2 and R_3, there is a delay in the R_2 operation time will occur regarding to the fault current sets in the R_2 definite region past the PSM_{max}. The selectivity of the OCR scheme will be affected by extending resulting CTI between both OCRs eventually. Therefore, the limitation of the OCR characteristics curves should be taken into account in the optimization procedure to attain an optimal coordination between the protective relays.

- Impacting DG source on over-current coordination scheme in DNs:

The level of the short-circuit currents in the MG often varies depending on the level of penetration and the intermittent nature of the DG's based on renewable energy. The electricity supply from the upstream grid into user populations in the delivery feeders fluctuates greatly. The position and scale of DGs can mitigate the upstream grid 's contribution to fault currents in the downstream MG if a fault occurs. Since the degree of the short circuit depends on the grid impedance determined to the position of the fault, synchronization of OCRs in the presence of a DG can be compromised. The selection of appropriate TMS for each OCR in respect of PSM_{max} must be considered because of the limited industrial region OCRs curves. In case of excessive fault currents exceeding PSM_{max}, the subsequent sections will evaluate and explain the impact of DG sources on the coordination of the OC scheme without account of the capabilities of industrial OCRs curves.

When a DG_1 is configured in primary-backup synchronization between upstream and downstream circuits at the Figure 5.1, the operational time may be extended, allowing for a prolonged duration of short-circuit current, thus affecting the integrity of the system network and the thermal capacities of the device. As seen from Figure 5.1 for DG_1 situated between the primary and backup circuits when a problem happens downstream of OCR_1 (point F2), the backup currents and primary circuits are shown in Figure 5.3.

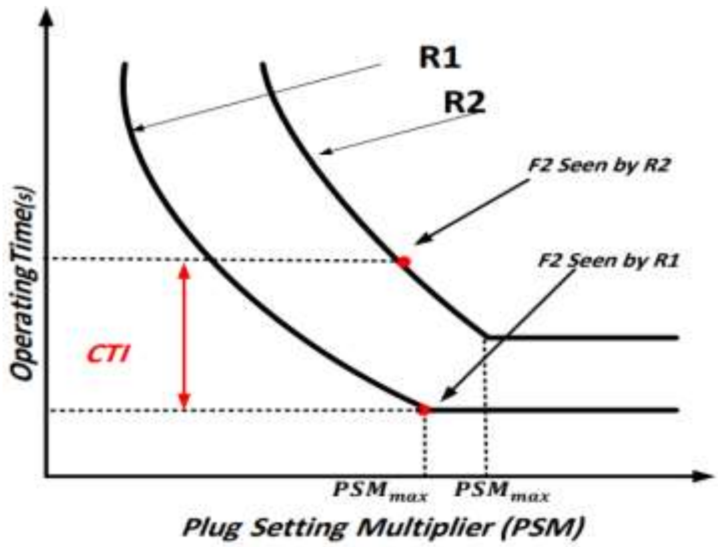


Figure 5.3: The primary and backup OCRs characteristics curves with DG1

Primary and backup OCRs features curves with DG_1 various and can be measured with Equations 5.2 and 5.3, and as:

$$I_p = I_{\mathrm{U}} + IDG_1\left[\frac{Z_1 + Zf}{Zt}\right] \tag{5.2}$$

$$I_b = I_{\mathrm{U}} + IDG_1\left[\frac{Z_1 + Zf}{Zt}\right] \tag{5.3}$$

where IDG_1 is the introduced current from the DG_1, Z_1 is the impedance between the primary relay and the DG_1 source, Z_f is the impedance between the I_{p} and the fault location plus the fault resistance.

DG_1will make a significant contribution to the fault current depending on its closeness to the fault location. As a result, the current fault contribution from the upstream grid outlet will be reduced. Based on Equations 5.2 and 5.3 and the contribution from DG_1, I_b will be reduced as I_{p} increases.

The fault current will go above 20 times PSM into the specific area of primary R_1 tripping features. There would be a gap in R_1's running period, for the additional rise in the fault current. Reducing the fault current created because of the upstream network's source will reduce R_2's operating time. As a consequence, the CTI would be further decreased for both OCRs, increasing the time required to separate the faulty segment.

Figure 5.3 illustrates the normal inverse characteristics of the IEC. When a three-phase fault happens, and DG_1 is linked to the MG, primary R_1 trips the fault first. The R_2 backup will work if R_1 fails to trip the fault between the two OCRs following the predefined CTI. The fault current may achieve a higher value than the PSM_{max} of the specified OCRs in the feeder, due to the involvement of DG_1 to the fault. Therefore, despite the rise in short-circuit frequency, the running period of the corresponding OCRs does not change. The high DG_1 contribution and the significant decrease of the upstream network participation will increase substantially the CTI between the two OCRs, and the selectivity of the OCRs security system would undoubtedly have an effect.

- Impacting of DG Existence Upstream from the Primary and Backup Relays

Figure 5.1 Indicates upstream involvement of DG_2 from both the main and backup OCRs. In case of a problem, the integration of DG_2 will boost the defect current level. Even though, both OCRs would experience the same current downstream in case of fault attack. The disparity in the PSM of each OCRs, R_1 and R_2, creates problems of mis-coordination as the highest PSM for the lower pickup current setting is surpassed by the fault current value. As in the following equations, the measured currents can be expressed through both OCRs (Fani, Bisheh, & Sadeghkhani, 2018):

$$I_b = I_P = I_{\mathrm{U}} + IDG_2 \left[\frac{Z_1 + Zf}{Zt} \right] \quad (5.4)$$

The primary and backup relay pairs entered the delay stages of the definite region of the OT due to increasing in the short circuit. As a result of PSM for both relays surpass twenty times of backup current, which would reduce the CTI between the main and backup OCRs. In these cases, changes in the fault current rate may occur as a pause in the main OCR operational period thus extending the replacement OCR's operating time. Finally, the un-selectivity between the main and backup OCRs is impaired.

5.3 Optimal Protection Coordination Considered PSM Constraint

In this part, a mathematical model is constructed to apply in industrial relays considered the maximum PSM to comply with their limits and constraints. The speedily prevention the unnecessary power outage is the primary purpose of studying the OCRs coordination. In Chapter 4; subsection 4.3.1, namely Equations 4.3, 4,5, 4,6 and 4,7 have been described the coordination problem formulation generally. A new constraint has been added to the previous mentioned equations, which is considered the essential equation it this chapter, more details can be shown as below:

- Bunds on the relay plug setting multiplier.

Incarnating the limitation in the industrial OCRs tripping characteristics requires solving the problem of coordinating OCRs. Authors in (Saad et al., 2019) proposed a new constraint and constructed a mathematical formulation taking into account the greatest PSM of used commercial OCRs. The enhancement of the optimization techniques performance for optimum OCR settings is the main goal. As has been mentioned before, the minimum and maximum operating region of PSM for currently OC protective relays is commonly adjusted between 1.1 and 20. Then, the boundaries and limits in the optimization technique can be formulated as follows:

$$PSM_{min} \leq PSM_j \leq PSM_{max} \tag{5.5}$$

where PSM_{min} and PSM_{max} are the minimal and maximal PSM values of relay R_j

Equation 5.5 contributes to solve the problem statement that has been described above, particularly, at high faults with existence of the DGs beside the main source in the MGs. Applying this equation and achieving its goal will be discussed and analysed in the simulation set-up and discussion section.

- Bunds on the relay plug setting.

$$PS_{min} \leq PS_j \leq PS_{max} \tag{5.6}$$

where PS_{min} and PS_{max} are in order of the minimal and maximal plug setting values of relay R_j.

- Bounds on the relay characteristics.

Related to IEC standard normally inverse characteristics (El-Fergany & Hasanien, 2017), in this study, the operation time is determined as follows:

$$t_{j,k} = \frac{0.14\, TMS_j}{[PSM_{j,k}]^{0.02} - 1} \tag{5.7}$$

5.3.1 The Non-Standard Characteristics Approach

Intelligent and adaptive protection schemes are the most important requirements of modern DNs. Therefore, finding coordination schemes adaptable to the new challenges imposed by modern DNs must be the aiming of the NSCs and user-defined characteristics of OCRs. In Chapter 4, a novel proposed non-standard time current characteristics approach based on algorithmic function has been introduced and approved for its reliability and effectiveness. In this context, a different non-standard characteristic approach (N-SCA) based on normal inverse IEC characteristics has been proposed in this chapter for the coordination of OCRs in MG, this proposed approach complements and improves the N-SC introduced in the literature survey in (Saad et al., 2019)-(El-Naily et al., 2019). This proposed N-SCA method is used based on a proposed HWCMFO technique together as a different solution for solving the OCRs coordination. As that illustrated in Figure 5.4, the proposed based upon adjusting the PSM_{max} to be 50 times instead of standard 20 times the OCR pickup current to transact with immoderate fault currents. The basic equation is used in this proposed scheme is Equation 5.5 that introduces a new constraint and constructed a mathematical formulated and outlines minimum and maximum operating region of PSM for currently OC protective relays for proposed N-SCA constrains. Figure 5.4 illustrates the using of the proposed N-SCA with the standard IEC normally inverse characteristic approach for the commercial relays.

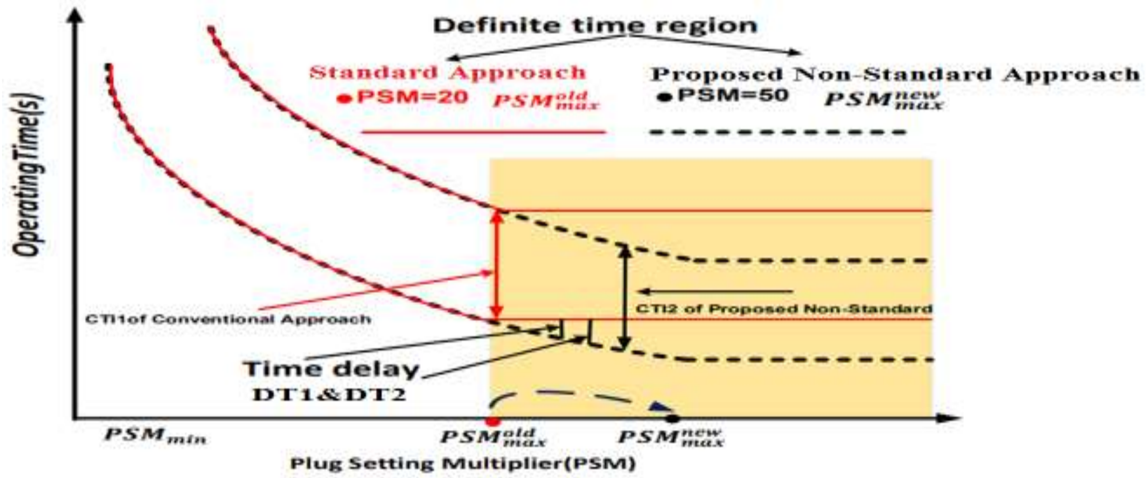


Figure 5.4: The primary and backup OCRs coordination of the proposed N-SCA

Figure 5.4 shows the use of the proposed N-SCA with the traditional or standard characteristics approach (SCA) without consideration of the PSM_{max} for the commercial relays. It can be noticed that with SCA application, the delay will occur in the operation time of primary OCR for a period time of (DT_1& DT_2) adding to more increasing with the fault current past the PSM_{max} of the standard IEC NI curve. Utilizing of the proposed N-SCA with PSM_{max}will extend to 50 instead of 20, then a reduction of the downstream primary relay operation time will happen and that will make CT_2 more available between paired the primary and backup relays when making a comparison with CT_1 of the SCA. Therefore, it raises the reliability and selectivity of the MG protection scheme. Currently, it becomes easy to program the user-defined tripping characteristics based on several operational modes of the MG and the nature of RESs of the DGs. Consequently, OCRs tripping characteristics can be defined instead of the predefined characteristics by applying the proposed N-SCA.

5.4 A Proposed hybrid algorithm based on Water Cycle Mouth Flame Optimization (HWCMFO)

Creating hybrid heuristic algorithms will significantly enhance the benefits of traditional techniques. These hybrid algorithms tend to be more robust and efficient compared to the basic versions they derive from, as they can leverage the strengths of multiple heuristic algorithms (Khalilpourazari & Khalilpourazary, 2017). A WCA was first proposed by (Eskandar et al., 2012). It is a heuristic method that simulates the natural water cycle and is built on strong conceptual foundations, enabling it to tackle optimization challenges efficiently. On the other hand, the MFO, developed by (Mirjalili, 2015) uses this process and mathematical modeling in its application. This study is driven by the aim to explore a successful hybridization of WCA and MFO that leverages the advantages of both algorithms within HWCMFO, as inspired by (Khalilpourazari & Khalilpourazary, 2019). HWCMFO offers notably stable and effective solutions for complex optimization challenges. One such challenge is the MG protection coordination issue. Therefore, utilizing HWCMFO can ensure relay selectivity and achieve optimized TMS relay settings for the MG. The next subsections explain the formulation module for the proposed HWCMFO algorithm. The WCA is deemed the basic algorithm in the suggested HWCMFO algorithm, which uses the moths' spiral movement to monitor stream and river location.

- Initialization

To initialize the HWCMFO algorithm, the WCA includes an array called stream like in most metaheuristic algorithms to display the design parameters of an optimization problem in the following manner.

$$\text{Raindrope} = [x_1, x_2, \dots \dots \dots, xn] \tag{5.8}$$

where x_1,,x_2, ..., xn refers to differential equations and n refers to the number of decision variables.

WCA has become a metaheuristic algorithm based on population; thus, a set of streams should be created as follows at the start:

$$\text{Raindrope Population} = \begin{bmatrix} x_1^1, & x_2^1, & \dots, & x_{N_{var}}^1 \\ x_1^2, & x_2^2, & \dots, & x_{N_{var}}^2 \\ \vdots & \vdots & \vdots & \vdots \\ x_1^{N_{pop}}, & x_2^{N_{pop}}, & \dots, & x_{N_{var}}^{N_{pop}} \end{bmatrix} \tag{5.9}$$

where N_{var} is the decision variable numbers, N_{pop} is the population numbers and the number of rows in the initial population is equivalent to the number of streams, which is also the input variable of the algorithm.

- Creation of sea, river and stream

The cost function value for each stream is determined by using the WCA in this step as follows,

$$\text{Ci} = Cost_i = [X_1^i, X_2^i, \dots \dots \dots, X_{N_{var}}^i] \text{ i=1, 2, 3, ..., } N_{pop} \tag{5.10}$$

where C_i and Cost_i are the cost function value, $[X_1^i, X_2^i, \dots \dots \dots, X_{N_{var}}^i]$ is an intimal population matrix. Because each stream updates its location against its respective river, unless the objective feature of the stream in its current position is greater than its subsequent river, the WCA adjusts the direction of the stream and river. Remember that the WCA uses the same method for updating the rivers' location toward the sea.

- Flow intensity determination

The WCA allocates streams to rivers and sea based on the level of the flow defined as NS_n which using the formulation below:

$$\text{NS}_\text{n} = \text{round}\left\{\left|\frac{\text{Cost}_\text{n}}{\sum_{i=1}^{N_{sr}} \text{Cost}_i}\right| \times N_{Raindrops}\right\},\ n = 1, 2, \dots \dots, \text{N}_\text{sr} \tag{5.11}$$

where $\mathrm{N_{sr}}$ is the totalize of rivers and a single sea. $\mathrm{N_{raindrops}}$ is considered as streams, which is equal $\mathrm{N_{pop}} - \mathrm{N_{sr}}$.

Formation of streams, rivers and sea mostly in second stage, the WCA determines the optimal value within each source in the current population, then lists the waterways from the better to some of the worst with regard to their respective objective function value and assigns the best stream (1st in the sorted community) as the shore. The second source to N_{sr}− 1st is regarded as rivers. The remaining ones ($N_{pop} - N_{sr}$) are treated as streams.

- Exploitation stage

For increasing exploitation performance, the MFO's exploitation phase has been used with WCA as following spiral Equation:

$$x_{\mathrm{stream}}^{\mathrm{i+1}} = \left|x_{\mathrm{stream}}^{\mathrm{i}} + \mathrm{sea}\right| \times e^{bt} \times \cos(2\pi \mathrm{t}) + sea \tag{5.12}$$

where the spiral shape of the moth flame is represented by the constant b, *t* refers to a random value between -1 and 1 that contributes to identifying the following stream closest position to the sea.

- Levy flight addition

The WCA iterations are fundamental in the WCA algorithm, if the streams modify their locations and are unable to find a better solution, then the location of the rivers and the sea would not change until the following iteration. In HWCMFO, to boost the randomness of the algorithm, streams are allowed to update their position using Levy flight using the following equation.

$$x_{i+1} = x_i + Levy(dim) \otimes x_i \tag{5.13}$$

where $\mathrm{x_{i+1}}$ is the following stream position, xi is the current stream position and dim is the problem dimension or the decision variables number. The next formula is used to calculate the Levy flight (Khalilpourazari & Khalilpourazary, 2019).

$$Levy(x) = \frac{0.01 \times \sigma \times r_1}{|r_2|^{\frac{1}{\beta}}} \tag{5.14}$$

where r_1 and r_2 are numbers generated from 0 to 1 randomly, σ and β are scaling parameters (Yang, 2010).

- Evaporation state

In WCA the parameters of evaporation and rain are avoided to reduce stagnation in local optima and to improve randomization. Evaporation and runoff start when there is less than $\mathrm{d_{max}}$ space between a river and the sea. ; This method often takes place when the distance from any source to the sea is far less than $\mathrm{d_{max}}$ (Sadollah, Eskandar, Bahreininejad, & Kim, 2015). A huge proportion for d_{max} should be deemed in order to concentrate more on discovery, while a low amount for $\mathrm{d_{max}}$ is preferred for production. Therefore, because the d_{max} value should be high in the first instance to focus mostly on discovery, and over the last iterations it must be low to leverage the solution space, the d_{max} size assumed to change over the iteration process (Khalilpourazari & Mohammadi, 2016). To this end, the following formula is being used to linearly reduce the $\mathrm{d_{max}}$value during iterations.

$$d_{\mathrm{max}}^{\mathrm{i+1}} = d_{\mathrm{max}}^{\mathrm{i}} - \frac{d_{\mathrm{max}}^{\mathrm{i+1}}}{\mathrm{Max\ I_t}} \tag{5.15}$$

where $\mathrm{d_{max}}$ is an insignificant number and Max It points out towards the maximum number of iterations. Raining process takes place when the distance between such a river or stream as well as the sea is below $\mathrm{d_{max}}$ in order to develop new streams that flow into rivers and sea. This process takes place sequentially to satisfy the criteria for the stoppage.

- Convergence criteria

In the proposed HWCMFO algorithm, the convergence criteria is guaranteed both exploration and exploitation and is illustrated in the Equation 5.16 as follows.

$$a = 1 + Curren\ it\left(\frac{-1}{\mathrm{Max}\ it}\right) \tag{5.16}$$

where a is a convergence constant which over the process of iterations decreases linearly from − 1 to – 2, Current it is a currently iteration, Max it is the maximum number of iterations.

To more effectively explore the solution space during the first iterations and manipulate the optimal solution in the last iterations, an optimized method is suggested to decrease the ideals of the parameter t over its iterations (Khalilpourazari & Pasandideh, 2017) and shown in the following Equation 5.17.

$$Z = (a - 1) \times rand + 1 \tag{5.17}$$

where Z is an optimized parameter to obtain the optimal solution.

In the present chapter, the flowchart for the proposed HWCMFO algorithm is presented in Table 5.1.

Table 5.1: The Procedures of the HWCMFO Algorithm

Stages	**Explanation**
Stage 1: Setting	Setting the initial parameters N_{pop} , $\mathrm{N_{sr}}$, and max it.
Stage 2: Iinitialization	• Applying IEC MG model and calculating the short circuits. • Using the matrix in Equation 5.9 to generate the population.
Stage 3: Cost function determination	• The cost function of each stream is determined by using Equation 5.10. • Sorting the stream based objective function value to form sea, river and streams using $\mathrm{N_{sr}} = revirs\ number + 1(sea)$ and $\mathrm{N_{raindrops}} = \mathrm{N_{pop}} - \mathrm{N_{sr.}}$
Stage 4: Flow intensity determination	Using Equation 5.11 to determine the flow of intensity of stream to river and sea.
Stage 5: Exploitation	When all positions are exchanged to be equaled river position, the spiral movement updates the river position by using Equation 5.12.
Stage 6: Levy flight addition	Utilizing the levy flight function to update the stream position by utilizing Equation 5.13.
Stage 7: Evaporation state satisfied	Started the raining process and decreasing the $\mathrm{d_{max}}$ value by using Equation 5.15.
Stage 8: Convergence criteria checking	Finally, this process takes place sequentially to satisfy the criteria for the stoppage if the evaporation state is satisfied. If not, the optimization process will come back to stage 4.

The OCRs optimal setting were acquired offline only due to the time consumed to get optimum setting utilising HWCMFO optimization technique, affecting the tripping time of the OCR. In this study, two strategies have been implemented based on the HWCMFO algorithm in MATLAB are shown as follows,

1- The classical approach: acquiring TMS values by using the proposed HWCMFO algorithm with taken into account $PSM_{old\ max}$, this approach has have been applied in the OCRs using IEC normally inverse curve with PSM range between 1.1 and twenty.

2- Employing the suggested HWCMFO algorithm with proposed N-SCA, which extended from $PSM_{old\ max}$ 20 to be $PSM_{new\ max}$ 50. Its adjusting and programming are easy in the numerical relays providing by numerous industrialists (Coleman, Branch, & Grace, 1999).

An IEC MG benchmark is carried out in NEPLAN package (2019 version) for extensive analysing and investigating for the performance of both approaches. Lastly, evaluation and investigation of CTI and the overall operation time, OT of the two approaches that have been mentioned above are implemented to prove the effectiveness and usefulness of the proposed approach. In addition, PSO algorithm is used in this chapter for the comparative purpose to prove the effectiveness and reliability of the HWCMFO algorithm.

- *Implementation of the HWCMFO Algorithm*

In the optimization procedure of the proposed HWCMFO algorithm, the CTI between the primary relay and backup relay is set at 0.3s as illustrated in Chapter 4, in Equation (4.5). As shown in Equation 4.6, the bounds of TMS are set between 0.05 and 3 (lower and upper limits). According to Equation 5.7, the constraints of OCR operating period are set from 0.1s to 1.1s (Saha, Datta, & Das, 2016). At each mode, there is a single OF and a known number of CTI constraints are considered in the following subsections. The proposed HWCMFO code is implemented in MATLAB. An IEC MG benchmark has been used to test the suggested hybrid technique with a population size of 80 and 350 iterations. For two cases (N-SCA and SCA) and four modes, the HWCMFO had been tested 40 times and the lowest OF values were recorded 4.89 in mode 1, 6.21 s in mode 2, 10.76 in mode 3 and 14.20 in mode 4 as are shown in the next section 5.4 in Table 5.3.

- *PSO Algorithm*

The PSO is a heuristic technique of random optimization designed by (H. H. Zeineldin et al.), who were influenced by the simulation of circling bird flocks' intelligence. PSO shares many features with evolutionary methods such as GAs. A population of viable random solutions initializes the problem; however, PSO does not contain any genetic operational activities, such as crossover or mutation. PSO has been widely applied in several fields over the past few years (Lin, Chen, & Gaing, 2010) & (Niknam, Mojarrad, & Nayeripour, 2011). PSO's results have been proven superior to other methods. Below is a review of the PSO procedure.

- Initialization. It produces a swarm of possible alternatives, called "particles," randomly assigning a speed to each.
- Velocity Update. Then the particles are "transported" through hyperspace, by modifying their own speed. A particle's velocity update is dynamically adjusted, subject to its own past flight and that of its allies. The following equations calculate the velocity and the location of the particles:

$$V_{id}^{new}(t+1) = c_o \times V_{id}^{old}(t) + c_1 \times \left(p_{id}(t) - x_{id}^{old}(t)\right) + c_2 \times \left(p_{gd}(t) - x_{gd}^{old}(t)\right) \tag{5.18}$$

$$c_o = 0.5 + \frac{rand}{3} \tag{5.19}$$

$$x_{id}^{new}(t+1) = x_{id}^{old}(t) + V_{id}^{new}(t+1) \tag{5.20}$$

where c_o is an inertia weight, $c_1\ and\ c_2$ are positive constants and rand is a random value from 0 to 1. Equation 5.18 shows the new velocity calculation for each individual. According to previous velocity $V_{id}(t)$, the velocity for each particle is updated, $p_{id}(t)$ is the particle's previous best location and $p_{gd}(t)$ is the global best location. The maximum velocity Vmax is clamped to particle velocities for each dimension. Equation 5.20 represents the updating of each particle's position in the research space. Implementation of the PSO flowchart is shown as order stages as follows,

- Stage 1: Reading system data and defining initial population.
- Stage 2: Computing objective function.
- Stage 3: Computing $p_{id}(t)$ and $p_{gd}(t)$.
- Stage 4: Updating $V_{id}^{new}(t+1)$ and $x_{id}^{new}(t+1)$.
- Stanot,5: Examination the stopping criteria, if it met then the optimization process can be ended, if not it will come back to stage 2.

The next subsection is illustrated the simulation set-up and discussion of the proposed HWCMFO algorithm application. Besides, the SCA and the N-SCA with the extended $PSM_{old\,max}$ to 50 instead of 20 time based on the suggested hybrid technique. Eventually, a comparison between HWCMFO and PSO algorithms in terms of tripping times, iterations, and optimization time.

5.5 Simulation Set-Up and Discussion

The coordination problem issues are tackled by using NEPLAN software. A radial network, an IEC MG benchmark tied to different types of DG technology (PowerStation, 2001) is used in this chapter to implement the proposed approach. Figure 5.5 illustrates the flowchart of work and the stages have been followed in this section. Initially, setting the relay via achieving the load flow. Afterward, for different four modes in the IEC MG, the fault currents in different locations are calculated according to IEC 60909 (Sweeting, 2011) as that shown in the Table 5.2.

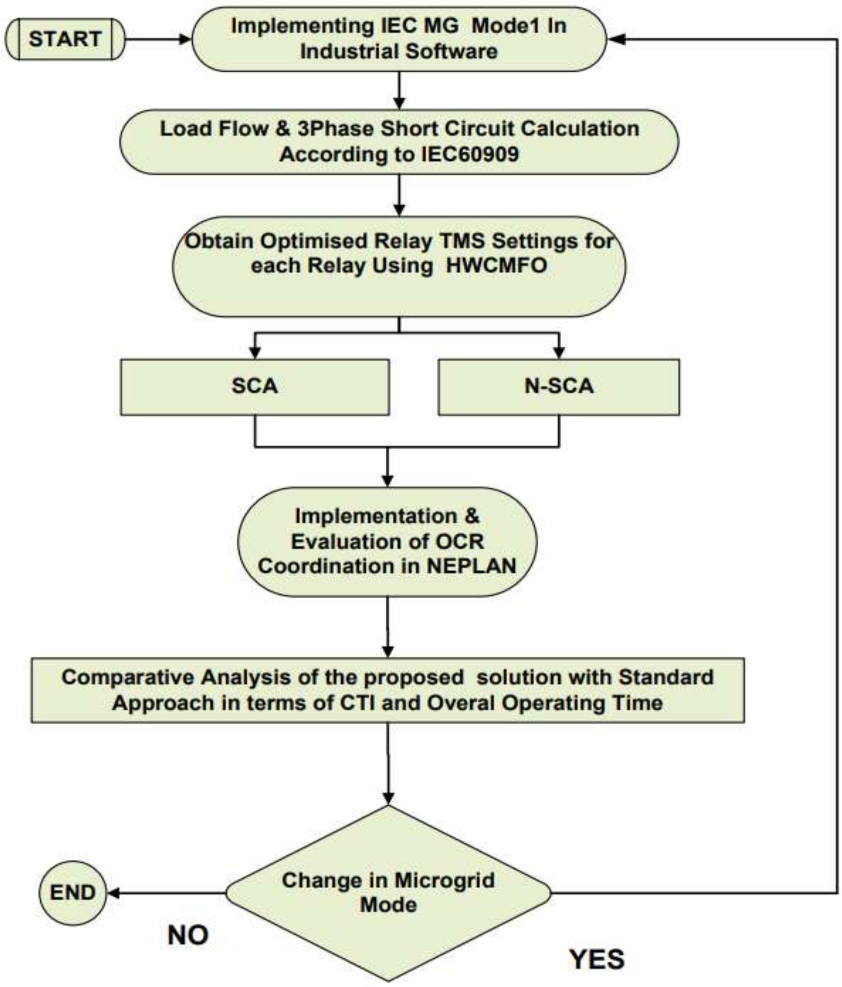


Figure 5.5: The flowchart of the work

Table 5.2: MG Operations Modes

Modes	Grid	DG1	DG2	DG3	DG4
Mode 1	ON	OFF	OFF	OFF	OFF
Mode 2	ON	ON	OFF	ON	OFF
Mode 3	ON	ON	ON	ON	OFF
Mode 4	OFF	ON	ON	ON	ON

In different locations during four different operating modes, the simulation for three-phase faults had been executed. Figure 5.6 illustrates a standard IEC MG arrangement connecting DGs. The IEC MG details are giving in the subsection 4.1.1 in Chapter 4 and (Kar, Samantaray, & Zadeh, 2017) Appendix A.

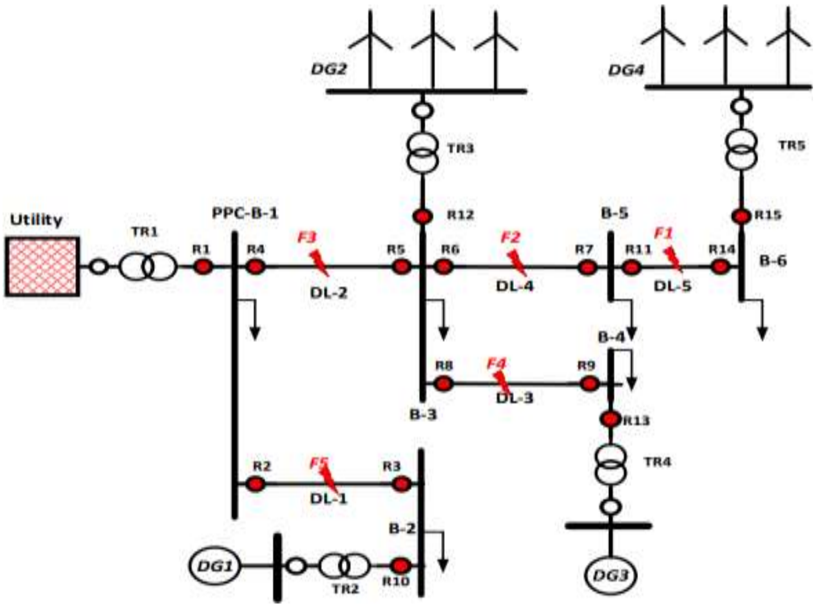


Figure 5.6: An IEC MG Benchmark

A hybrid technique in optimization approach has been carried out for solving OCRs problem newly. In addition, an N-SCA considering a problem appeared during testing our result also had been implemented. A comparison analysis between the conventional approach and the N-SCA in terms of overall operation time and coordination criteria indexing was achieved. For each operation typology, an objective function in HWCMFO method had been analyzed and formulated by the coordination problem formulation and obtaining the optimal OCRs setting. In the simulation set up, the work- flow had been followed by implementing some steps that to analyze and investigate the effectiveness of the proposed approach, these steps are described as below,

- Initially, set the OCRs to determine the CTR and PS for each OCR that performs the load flow as shown in Table 5.3 below.
- According to IEC 60909 (Castillo Salazar, Conde Enríquez, & Schaeffer, 2015), a short-circuit calculation for the fault currents in various locations for the four different MG operation modes in Table 5.2 were applied.
- The proposed methodology was used to obtain the optimum setting of OCRs, it was achieved offline because the tripping time of OCRs could be affected by the time consumed to obtain the optimized TMS.
- Lastly, over all operation time, OT and CTI of the N-SCA and SCA had been investigated and evaluated to verify the effectiveness and usefulness of the proposed approach.

An IEC MG implemented in NEPLAN Package is represented by the simulated network illustrated Figure 5.6. It consists of four DGs with various technology types and 15 OCRs. This chapter considers four different scenarios. Table 5.2 represents the network configuration and the state of DGs. For setting the CTR and PS of the fifteen OCRs in the network based on the loading capacity in the network, the load flow calculations had been performed. For configuring the setting of the protective relays, a short-circuit calculation for different lines was calculated for each mode in this study. The levels of three-phase faults at different transmission lines in the MG are illustrated in Figure 5.6. These faults can be represented as a fault on the line DL-5, named F1; a fault on the line DL-4, named F2; a fault on the line DL-2, named F3; a fault on the line DL-3, named F4; and a fault on the line DL-1, named F5. Figure 5.7 shows the levels of the fault current for the faults that had been created in the four modes.

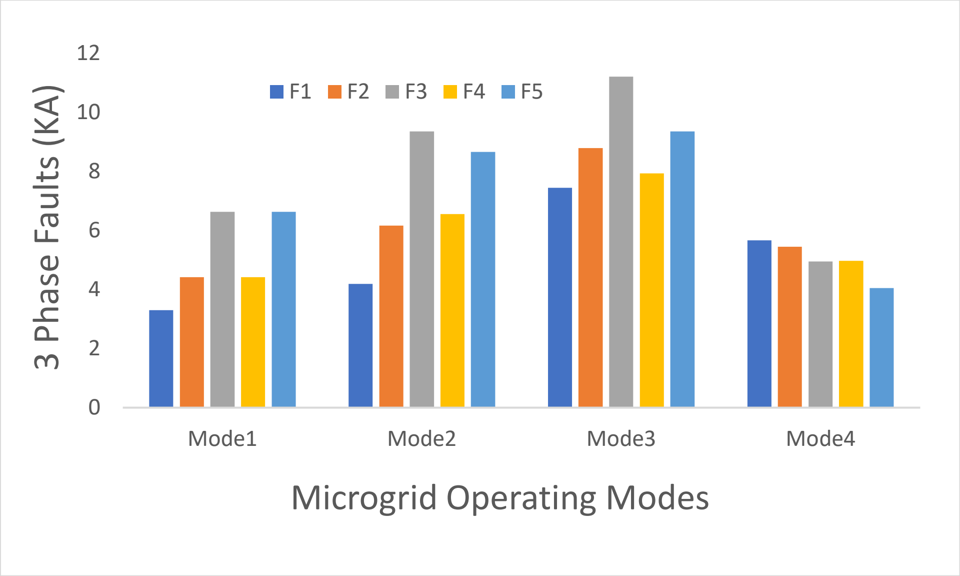


Figure 5.7: Short-Circuit Level in Different Operational Modes for Different Locations

Fault F3 due to its location on the line DL-2 which is nigh from the main source as well as the involvement of all the DGs, it generates the maximum fault current in modes 1,2 and 3 respectively which are 6631A, 9348A and 11198A. Due to the absence of the main grid source in the mode 4 (Islanding mode), all the levels of the fault current are significantly less than the other three modes. The maximum fault current is 5658 A that happened on the line DL-5 at fault location F1.

Table 5.3 illustrates the TMS obtained for each OCR in each mode and the values of the CTR and PS for each OCR. It acquired with the optimal setting from each approach for two processes: the SCA and the proposed N-SCA by MATLAB, which they are implemented in industrial OCR in NEPLAN software.

Table 5.3: Optimized TMS and PS for all OCRs for Different Operational Modes using HWCMF Algorithm.

Relays	CTR	PS	HWCMFO Algorithm							
			Mode 1		Mode 2		Mode 3		Mode 4	
			N-SCA	SCA	N-SCA	SCA	N-SCA	SCA	N-SCA	SCA
R1	1200	1	0.223	0.247	0.203	0.248	0.214	0.249	/	/
R2	400	0.5	0.05	0.05	0.05	0.050	0.05	0.05	0.050	0.050
R3	400	0.5	/	/	0.05	0.05	0.05	0.0508	0.201	0.201
R4	400	0.5	0.310	0.306	0.300	0.315	0.299	0.316	0.136	0.136
R5	400	0.5	/	/	/	/	0.052	0.05	0.171	0.171
R6	400	0.5	0.173	0.174	0.185	0.183	0.185	0.183	0.159	0.159
R7	400	0.5	/	/	/	/	0.141	0.14	0.232	0.232
R8	400	0.5	0.05	0.05	0.05	0.05	0.05	0.050	0.05	0.05
R9	300	1	/	/	0.05	0.050	0.056	0.050	0.134	0.134
R10	400	0.5	/	/	0.086	0.086	0.085	0.086	0.198	0.197
R11	300	1	0.05	0.05	0.050	0.05	0.05	0.05	0.050	0.050
R12	300	1	/	/	/	/	0.132	0.131	0.144	0.144
R13	400	0.5	/	/	0.086	0.087	0.091	0.086	0.148	0.148
R14	300	1	/	/	/	/	0.272	0.271	0.346	0.346
R15	400	0.5	/	/	/	/	0.338	0.336	0.401	0.401
OT(s)	/	/	4.89	5.22	6.21	6.84	10.76	11.40	14.20	14.25

The optimum setting obtained for N-SCA is compared with the technique considering 20 times the maximum PSM taking into account the CTI between primary and backup relay pairs and the overall operational time for various fault locations in the four operational modes. From Table 5.3, it can be noticed that the TMSs values in all modes for the proposed strategy are lower than TMSs values of the SCA. In addition, the overall operation times of the proposed scheme are also lower than the overall operation times of the conventional scheme. As a result, the N-SCA approves of its effectiveness and usefulness.

5.5.1 IEC MG Simulation Results based on HWCMFO Algorithm

This section presents and discusses the impact of DGs presence on the IEC MG benchmark in different four modes as illustrated in Table 5.2 under various faulty locations that are shown in Figures 5.6 and 5.7. In addition, it illustrates and analyzes the outcomes of the simulation on MATLAB and NEPLAN software in terms of the impact of the fault position and its failure to be in the definite region by using IEC NI curve for the OCRs and using the N-SCA with the new PSM for solving this coordination problem.

5.5.1.1 IEC MG Simulation Results in Mode 1

For different faults simulation performed in this topology, the feeding source of the MG is the main grid only. It has been noticed in this case that some fault currents override the maximum PSM for the OCRs utilized in the grid. Each OCR sees the short circuit currents are illustrated in Table 5.4 as follows,

Table 5.4: Fault Currents in Mode 1

Fault Location (FL)	3 Phase Symmetrical Fault (A)				
	Primary Relays (PR)		Backup Relays (BU)		
	PR1	PR2	BU1	BU2	
F1	R11 3303	R14 ----	R6 3303	R15 ----	
F2	R6 4415	R7 ----	R4 4415	R14 ----	R12 ----
F3	R4 6631	R5 ----	R1 6631	R7 ----	R12 ----
F4	R8 4415	R9 ----	R4 4415	R13 ----	
F5	R2 6631	R3 ----	R1 6631	R10 ----	

At fault F2, the measured values of the PSMs for both primary R6 and backup R4 are 22.075 and 22.075 in order. The great F2 level will surpass the maximum PSM of the appointed OCR. Consequently, Due to the fault position will fall in the definite region for R4 and R6, there is a delay in the operation time of the two relays will be occurred. In case of fault F3, the same situation will happen for the fault seen just by the primary R4 which is 33.155 PSM. At the fault F4, the fault seen by the primary R8 and backup R4 are 22.075, and 22.075 PSM respectively. Between both, the small CTI will result in mis-coordination due to delaying the tripping time R8 since the fault current exceeds the maximum PSM of R8. The case of the fault F5 is the same of the fault F3 that only the fault seen by the primary R2 which is 33.155 PSM that exceeding the maximum PSM. As a result, the miscoordination problem will be avoided and the selectivity of the overcurrent scheme will be insured in the MG. The operation time, OT of each related OCR using the standard technique and N-SCA have been presented in the Table. 5.5 as below:

Table 5.5: Operating time for all OCRs for mode 1

	Relay Operational Time (sec)									
	Proposed (N-SCA)					SC A				
	PR		BU			PR		BU		
FL	PR1	PR2	BU1	BU2		PR1	PR2	BU1	BU2	
F1	R11 0.12	R14 ----	R6 0.41	R15 ----		R11 0.12	R14 ----	R6 0.41	R15 -----	
F2	R6 0.37	R7 ----	R4 0.67	R14 ----	R12 ----	R6 0.41	R7 ----	R4 0.7	R14 ----	R12 ----
F3	R4 0.33	R5 ----	R1 0.7	R7 ----	R12 ----	R4 0.39	R5 ---	R1 0.7	R7 ----	R12 ----
F4	R8 0.12	R9 ----	R4 0.38	R13 ----		R8 0.11	R8 ----	R4 0.7	R13 ----	
F5	R2 0.09	R3 ----	R1 1.09	R10 ----		R2 0.11	R3 ----	R1 1.01	R10 ----	

From the NEPLAN software, Figure 5.8 illustrates a fault at F2 in line DL-4. It represents the proposed non-standard scheme considering the 50 PSM max and the standard IEC inverse characteristics of the industrial OCRs. When the traditional approach used to acquire the TMS for the OCR coordination in the MG, the primary R6 works firstly to insulate the fault at 0.41s as well as the backup R4 works at 0.7s. The fault current value for a fault at F2 is 4.415KA, the PSM is 22.075 which overrides the PSM max for R6 and the tripping time of the OCR R6 is delayed. Whereas, the proposed non-standard technique reduced the operating time, OT for the primary R6 from 0.41s to 0.37s and the backup R4 from 0.7s to 0.67s, which the CTI between both of OCRs R6 and R4 is 0.3s. This decrease will mitigate the mis-coordination in OCR and avoid the delay in OT.

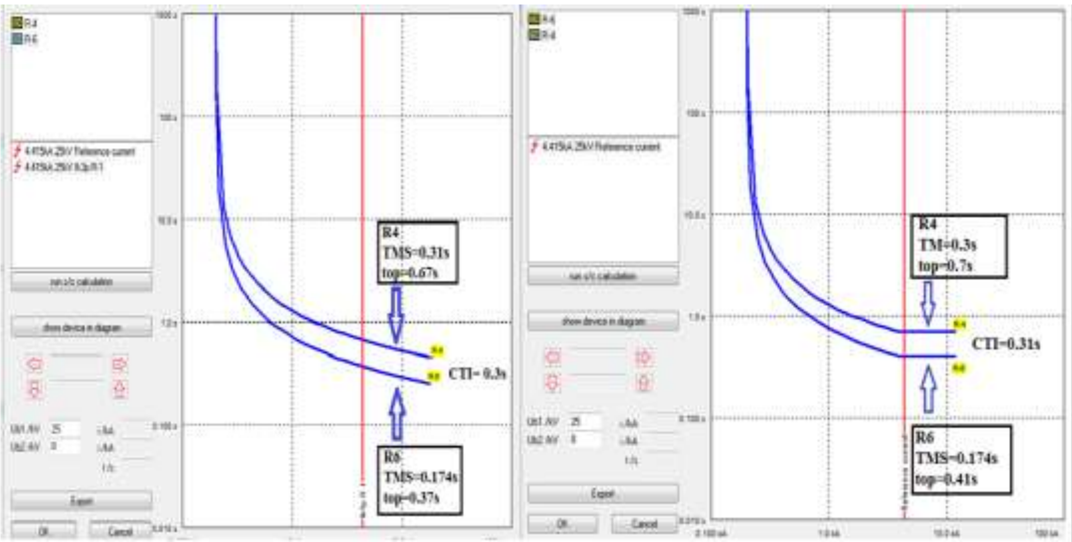


Figure 5.8: Performance assessment of primary R6 and backup R4 in mode 1

5.5.1.2 IEC MG Simulation Results in Mode 2

In the case of mode 2, only two SDGs, namely DG1 and DG3 are employed along with the source of the main grid with various faults mode within the MG. From Table 5.6, it is obvious that some of the fault currents values surpassed the maximum PSM due to the impact of two SDGs are connected and when a fault occurs, they lead to a fault magnitude. Consequently, the designated OCRs tripping time for these faults that have been in the define region which is behind the normal operation region of the inverse tripping characteristics.

Table 5.6: Fault Currents in Mode 2

Fault Location (FL)	3 Phase Symmetrical Fault (A)				
	Primary Relays (PR)		Backup Relays (BU)		
	PR1	PR2	BU2	BU2	
F1	R11 4187	R14 ----	R6 4187	R15 ----	
F2	R6 6157	R7 ----	R4 4303	R14 ----	R6 6157
F3	R4 7130	R5 ----	R1 6462	R7 ----	R4 7130
F4	R8 5607	R9 944	R4 4420	R13 944	
F5	R2 7709	R3 944	R1 6262	R10 944	

The fault current levels for mode 2 in different locations are illustrated in Table 5.6. While the operating time of all OCRs for various faults locations in mode 2 are shown in Table 5.7 as follows,

Table 5.7: Operating Time for all OCRs for Mode 2

FL	Relay Operational Time (sec)									
	Proposed (N-SCA)					SC A				
	PR		BU			PR		BU		
	PR	BU	PR	BU		PR	BU	PR	BU	
F1	PR1	PR2	BU1	BU2		PR1	PR2	BU1	BU2	
F2	R11 0.11	R14 ----	R6 0.4	R15 ----	R11 0.11	R14 ----	R6 0.4	R15 ----	R11 0.11	R14 ----
F3	R6 0.36	R7 ----	R4 0.66	R14 ----	R6 0.36	R7 ----	R4 0.66	R14 ----	R6 0.36	R7 ----
F4	R4 0.57	R5 ----	R1 0.87	R7 ----		R4 0.57	R5 ----	R1 0.87	R7 ----	
F5	R8 0.1	R9 0.22	R4 0.66	R13 0.52		R8 0.1	R9 0.22	R4 0.66	R13 0.52	

At Fault F2, the primary R6 as 30.785 PSM is seen the fault current level of 6157 A. While the backup R4 as 21.515 PSM has been seen as the fault current level of 4303 A at F2. These results are owing to the position of DG1, DG3 and the main source in the grid. Therefore, there is a delay in the tripping time due to exceeding the fault current level to the maximum PSM. Figure 5.9 shows the operation of R6 and R4 in conventional technique and the proposed non-standard method, they will operate for the fault at F2 at 0.41s and 0.7 with CTI between them 0.29s in standard approach. The non-standard approach will decrease the operation time of the OCRs R6 and R4 to 0.36s and 0.66s respectively, which sustain the suitable CTI between them 0.3s. As a result, these values of the operation time of the OCRs R6 and R4 will mitigate the miscoordination in the OCRs. In addition, it can be noticed that the CTI between R8 and R4 at fault F4 is not = 0.3s. Similarly, between R2 and R1 at the fault F5, it is not =0.3s because of these faults are in happening at non-direct lines, while the F1, F2 and F3 have occurred at direct lines in the grid.

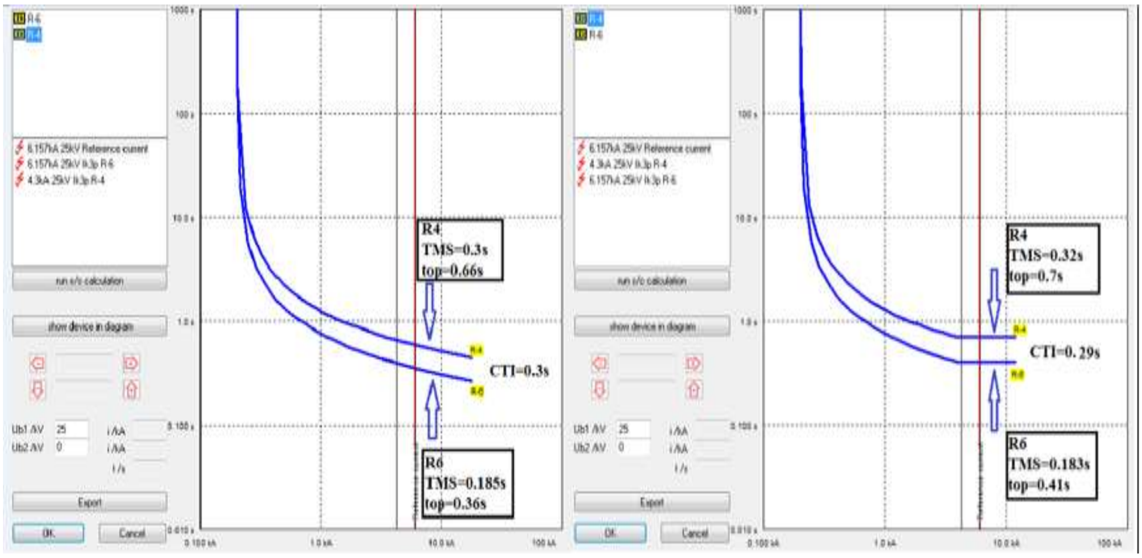


Figure 5.9: Performance assessment of OCRs R6 and R4 in mode 2

5.5.1.3 *IEC MG Simulation Results in Mode 3*

In this case, various fault modes have been implemented in the MG when all sources of the grid are connected, which are four DGs and the main grid source. DG1and DG3 are SDGs whereas G2 and G4 are wind Generation, IDGs. These DGs contribute a fault magnitude if the fault happens. From Table 5.8, it can be noticed that most of the fault’s values exceeded PSM_{max} that due to the existence of four DGs and their impact on the faults is significant. Then, the definite operating region of OCR's tripping characteristics is the location of the OCRs tripping time for those faults.

Table 5.8: Fault Currents in Mode 3

Fault Location (FL)	3 Phase Symmetrical Fault (A)				
	Primary Relays (PR)		Backup Relays (BU)		
	PR1	PR2	BU2	BU2	
F1	R11 4187	R14 3277	R6 4187	R15 3277	
F2	R6 6157	R7 2620	R4 4303	R14 2630	R6 6157
F3	R4 7130	R5 4071	R1 6462	R7 2024	R4 7130
F4	R8 6989	R9 944	R4 4124	R13 939	
F5	R2 8408	R3 944	R1 6018	R10 922	

The fault current levels for mode 3 in different locations are shown in Table 5.8. While the operating time of all OCRs for different faults in mode 3 are illustrated in Table 5.9.

Table 5.9: Operating Time for all OCRs for Mode 3

FL	Relay Operational Time (sec)									
	Proposed (N-SCA)					SC A				
	PR		BU			PR		BU		
	PR1	PR2	BU1	BU2		PR1	PR2	BU1	BU2	
F1	R11 0.11	R14 0.68	R6 0.4	R15 0.97		R11 0.11	R14 0.68	R6 0.4	R15 0.97	
F2	R6 0.36	R7 0.37	R4 0.67	R14 0.74	R6 0.36	R7 0.37	R4 0.67	R14 0.74	R6 0.36	R7 0.37
F3	R4 0.59	R5 0.11	R1 0.89	R7 0.41	R4 0.59	R5 0.11	R1 0.89	R7 0.41	R4 0.59	R5 0.11
F4	R8 0.1	R9 0.22	R4 0.7	R13 0.54		R8 0.1	R9 0.22	R4 0.7	R13 0.54	
F5	R2 0.09	R3 0.22	R1 1.15	R10 0.52		R2 0.09	R3 0.22	R1 1.15	R10 0.52	

For example, when a fault happens at F1, the current exceeded approximately 21 times the rated current of both primary R11 and backup R6 caused by contributing of the DG1 to the grid. Then, both relays have reached a given region and their trip time will therefore be delayed for a certain period. Similarly at fault F2, the current surpassed 31times the primary R6 as well as 21 the backup R4 rater current. Hence, both relays are in the definite region and their tripping time is delayed for a while. The same conduct occurred in the cases of fault F4. In the case of the faults F3 and F5, the current exceeded about 36 times the rated current of just primary OCR R4 at fault F3 and 42 times the rated current of just primary R2 at the Fault F5, however the rest of the OCRs are in the defined region.

Figure 5.10 shows the operation of the OCRs between the primary R4 and the backup R1with taken into consideration the standard characteristics and non-standard characteristics. At fault F3, they will operate at 0.7s and 1.02 respectively and the CTI between them is 0.32s in the standard characteristics. These operation time values will be decreased by applying the non-standard characteristics to 0.58s and 0.88s with CTI between them is 0.3s. Consequently, using the N- SCA to avoid the delaying time as that implemented in NEPLAN software in Figure 5.10 as follows,

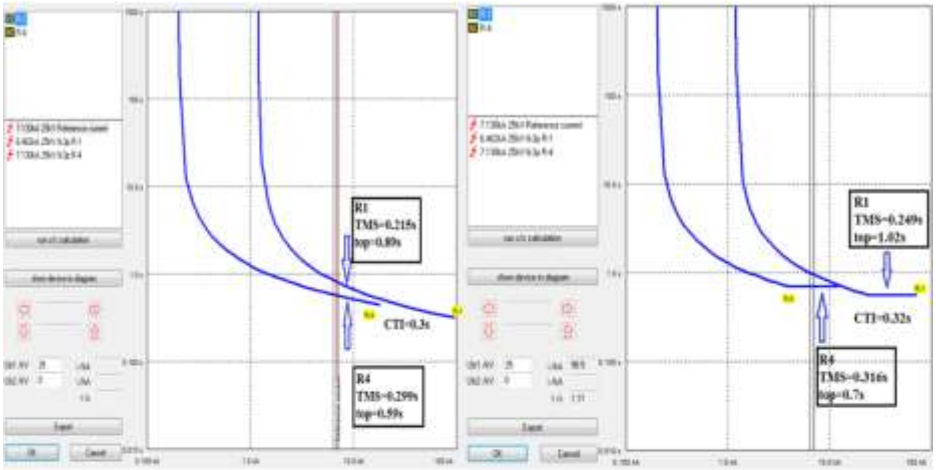


Figure 5.10: Performance assessment of OCRs R4 and R1 in mode 3

From Table 5.8 at fault F5, the measured currents in primary relays R2 and R3 are 8408 and 944 A, respectively, whereas the fault current have been measured by the backup relays R1, R10, are 6018 and 922 A, respectively. These notable changes in the values of the measured currents between the primary and backup relays affect the fault currents locus on the characteristics of the time–current for the pair of the primary–backup relays.

5.5.1.4 IEC MG Simulation Results in Mode 4

This case is an islanding mode where the IEC MG benchmark uses the four DGs as a feeder source and isolated from the main source feeder. Five fault simulations have been implemented in different locations. Compared to previous modes, the fault currents values are considerably lower in the islanding mode as illustrated in Table 5.10.

Table 5.10: Fault Currents in Mode 4

<table>
<tr><td rowspan="3">Fault Location (FL)</td><td colspan="5">3 Phase Symmetrical Fault (A)</td></tr>
<tr><td colspan="2">Primary Relays (PR)</td><td colspan="3">Backup Relays (BU)</td></tr>
<tr><td>PR1</td><td>PR2</td><td>BU1</td><td colspan="2">BU2</td></tr>
<tr><td>F1</td><td>R11
2387</td><td>R14
3277</td><td>R6
2387</td><td colspan="2">R15
3277</td></tr>
<tr><td>F2</td><td>R6
2914</td><td>R7
2630</td><td>R4
759</td><td>R14
2630</td><td>R6
2914</td></tr>
<tr><td>F3</td><td>R4
881</td><td>R5
4071</td><td>R3
881</td><td>R7
2024</td><td>R4
881</td></tr>
<tr><td>F4</td><td>R8
4029</td><td>R9
944</td><td>R4
723</td><td colspan="2">R13
944</td></tr>
<tr><td>F5</td><td>R2
3108</td><td>R3
944</td><td>R5
3108</td><td colspan="2">R10
944</td></tr>
</table>

For all the OCRs in the MG, they do not exceed 20 PSM times. Then, the NSC-A and SCA outcomes in this study remain the same. For instance, at fault F2, the fault current value will be 5544 A, while the measured values of both selected currents primary R6 is 2914 A and the backup R4 is 759A. Thus, they will not surpass PSM max, similarly, all the simulated faults.

The fault current levels for mode 4 in different locations are shown in Table 5.10. While the operating time of all OCRs for different faults in mode 4 are illustrated in Table 5.11.

Table 5.11: Operating Time for all OCRs for Mode 4

FL	Relay Operational Time (sec)									
	Proposed (N-SCA)					SC A				
	PR		BU			PR		BU		
	PR1	PR2	BU1	BU2		PR1	PR2	BU1	BU2	
F1	R11 0.14	R14 0.93	R6 0.47	R15 1.32		R11 0.15	R14 0.93	R6 0.47	R15 1.32	
F2	R6 0.43	R7 0.66	R4 0.73	R14 1.01	R6 0.43	R7 0.66	R4 0.73	R14 1.01	R6 0.43	R7 0.66
F3	R4 0.65	R5 0.38	R3 1.02	R7 0.74	R4 0.65	R5 0.39	R3 1.02	R7 0.74	R4 0.65	R5 0.38
F4	R8 0.11	R9 0.62	R4 0.75	R13 0.54		R8 0.11	R9 0.62	R4 0.76	R13 0.54	
F5	R2 0.12	R3 0.98	R5 0.42	R10 0.52		R2 0.14	R3 0.98	R5 0.42	R10 0.52	

From Table 5.10, it can be noticed that when the SCA and N-SCA are used in the islanded mode, there is a little difference between tripping time values in both cases that are due to the low fault current levels as that mentioned above in Table 5.11. Figure 5.11. depicts as an example fault F2 and its effect for primary R6 and the backup R4 with the N-SCA and the SCA as follows,

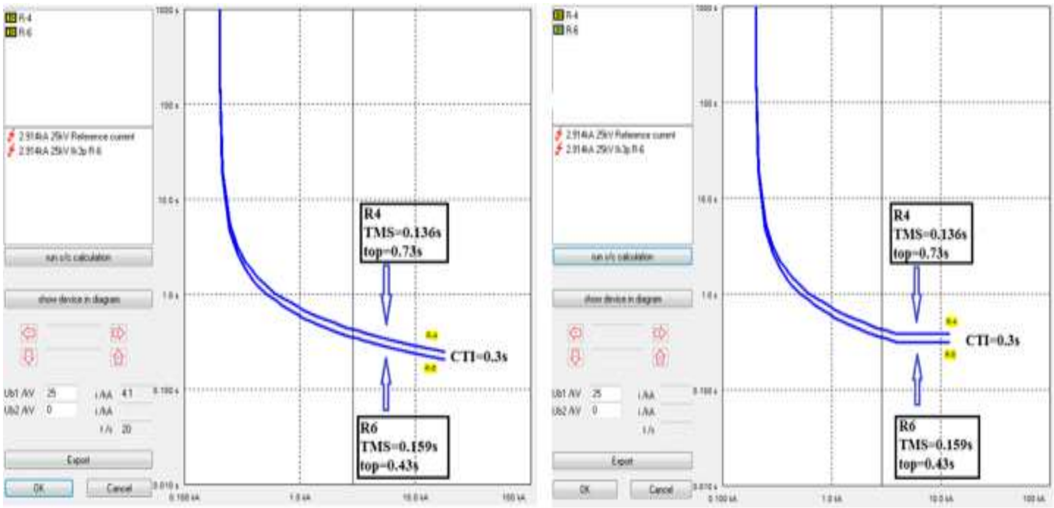


Figure 5.11: Performance assessment of OCRs R6 and R4 in mode 4

- Discussion of the radial IEC MG results.

It's worth mentioning that the HWCMFO technique was carried out to solve the coordination problem. The results gotten with this hybrid technique are compared with those mentioned in the Literature (Saad et al., 2019)- (El-Naily et al., 2019)-(Sergio Danilo Saldarriaga-Zuluaga et al., 2020a). Table 5.12 and Figure 5.12 demonstrate the overall operating time, OT attained with the applied technique. It is necessary to emphasize that in all analyses of the modes under consideration. For all operative modes, HWCMFO algorithm with considered the IEC limitations obtained satisfactory coordination as well as the lowest operation time among the others that reported in (Saad et al., 2019)- (El-Naily et al., 2019)-(Sergio Danilo Saldarriaga-Zuluaga et al., 2020a). Besides, the PSO technique is also used in this study for a comparative purpose as shown in subsection 5.4.3. The next table and figure present that the proposed HWCMFO algorithm with considering the IEC limitation (N-SCA) on the radial IEC MG benchmark reduced the overall OT of OCRs for all modes compared to (Saad et al., 2019)- (El-Naily et al., 2019)-(Sergio Danilo Saldarriaga-Zuluaga et al., 2020a). For instance, the HWCMFO technique reduced the overall OT in Mode 3 by 43.89%, 38.44%, 21.23% and 5.93% compared to the outcomes in (Saad et al., 2019), (El-Naily et al., 2019), (Sergio Danilo Saldarriaga-Zuluaga et al., 2020a) and PSO algorithm.

Table 5.12: Different Techniques Comparative Performance

Modes	(Saad et al., 2019)	(El-Naily et al., 2019)	[GA (Sergio Danilo Saldarriaga-Zuluaga et al., 2020a)]	[PSO]	[HWCMFO]
Mode 1	7.53	6.64	4.99	5.22	4.89
Mode 2	14.04	12.67	10.71	6.84	6.21
Mode 3	19.18	17.48	13.66	11.40	10.76
Mode 4	15.56	15.56	14.63	14.25	14.20

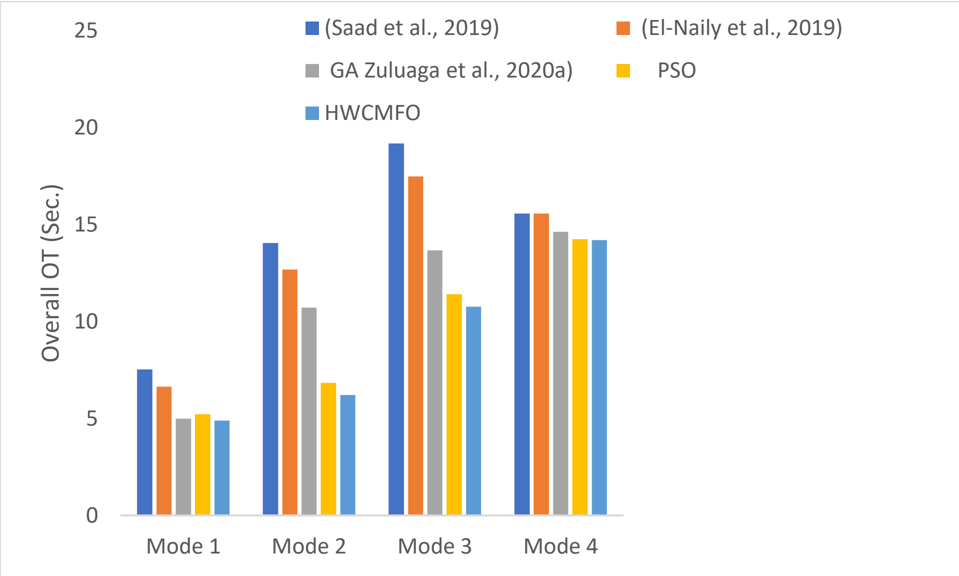


Figure 5.12: The overall OT in Modes 1, 2, 3 and 4

5.5.2 The HWCMFO algorithm convergence characteristics

This section shows the appropriacy of the proposed HWCMFO algorithm for OCRs coordination to find the global minimal OF values. The practical swarm optimization (PSO) is used in this section as a heuristic optimization technique for comparative purposes with the proposed hybrid technique. The comparison is in terms of tripping time, iteration number and the computational speed of the HWCMFO algorithm.

5.5.2.1 Comparison between HWCMFO and PSO in terms of convergence characteristics

The HWCMFO and PSO optimization techniques have been tested in MATLAB software, the outcomes of the convergence characteristics are demonstrated in Table 4.13. Four modes have been implemented and every mode has been runed forty times, the best fitness function values are adopted. The results show the reliability of the HWCMFO algorithm in terms of tripping time, calculation speed time for optimization process and fewer iterations compared to PSO algorithm.

Table 5.13: Optimized OT and calculation speed for different operational modes

	Mode 1	Mode 2	Mode 3	Mode 4
HWCMF OT (s)	4.89	6.21	10.76	14.20
PSO OT (s)	5.22	6.84	11.4	14.25
HWCMFO CPU Time(s)	1.01	1.30	0.86	1.23
PSO. CPU Time(s)	7.53	8.02	11.77	11.37
HWCMF Iterations	78	112	320	312
PSO Iterations	303	450	874	1000

Where CPU is a central processing unit that a time amount during the process of a computer program. It can be noticed that from the Table 5.13, the proposed HWCMFO algorithm considering limitation of IEC tripping characteristic outweighs the PSO algorithm. OCRs tripping times for all modes have been reducing by applying the proposed hybrid technique compared to PSO algorithm. In addition, obtaining the optimal solutions are taken just fewer iterations compared to PSO algorithm. For instance, in mode 2, the optimal solution of the HWCMFO has been obtained only after the 136th iteration, while it exceeds these iterations three times to get the optimal solution of the PSO algorithm. The optimized time done in HWCMFO algorithm at 1.3 s, whereas it done in PSO algorithm at 8.02.s.

- Evaluation of the HWCMFO algorithm and PSO algorithm in mode1.

In mode 1, the MATLAB software has been plotted the convergence characteristics for both HWCMFO and PSO algorithm, which just the main source operates without DGs. Figure 5.13 depicts these plots, the optimal solution of the HWCMFO algorithm was obtained at 4.893 s after only 78th iterations with just 1.01 s for optimization process. The proposed HWCMFO algorithm with considering limitation of IEC tripping characteristic compared to PSO algorithm, reduced overall OT in the IEC MG benchmark by 6.5% and reduced the iterations by 74.26%, which resulting to decrease the CPU time by 86.59%.

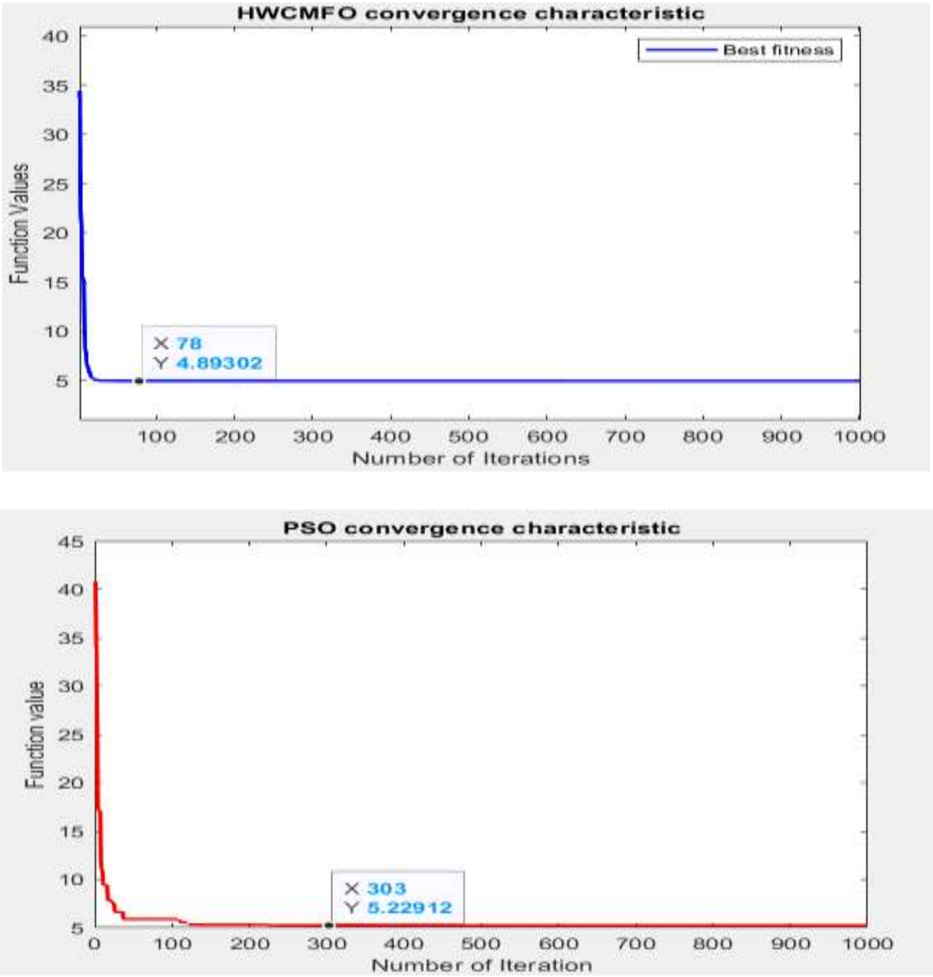


Figure 5.13: Evaluation of the HWCMFO algorithm and PSO algorithm in mode 1

- Evaluation of the HWCMFO algorithm and PSO algorithm in mode 2.

In this mode, with presents of the two SDGs with the main source, it is clear that in the Figure 5.14, the values of the fitness function of the PSO technique are becoming unstable until they reached 450th iterations, while they obtain the optimal solution at only 112th iterations when using the proposed HWCMFO technique. Thus, the HWCMFO technique maintains the reliability of the protection system.

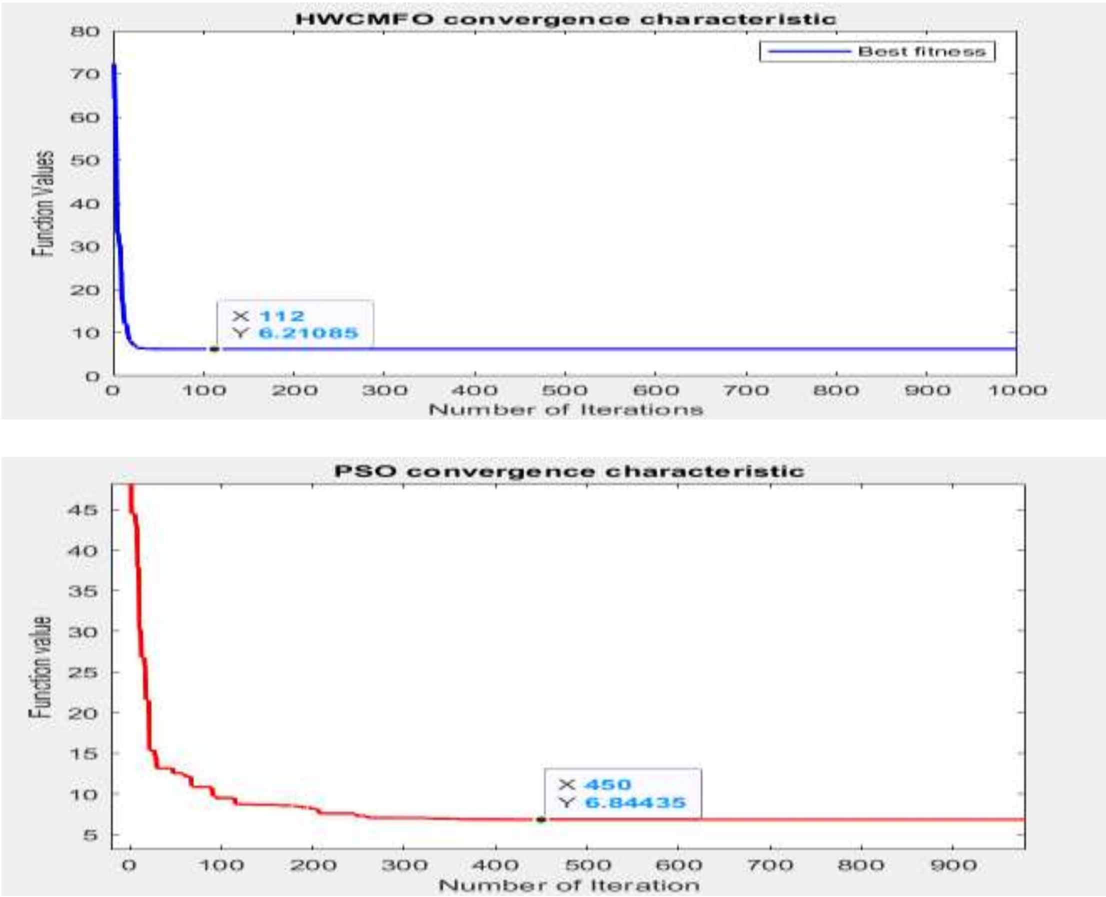


Figure 5.14: Evaluation of the HWCMFO algorithm and PSO algorithm in mode 2

- Evaluation of the HWCMFO algorithm and PSO algorithm in mode3.

In mode 3, all the DGs in the IEC benchmark operate with the main source. Figure 5.15 shows the differences between both plots, which the fitness function values of the PSO algorithm will be in the best fitness after 875th iterations. Yet, the best fitness function values of the proposed HWCMFO technique will be reached less than PSO technique by 63.39%.

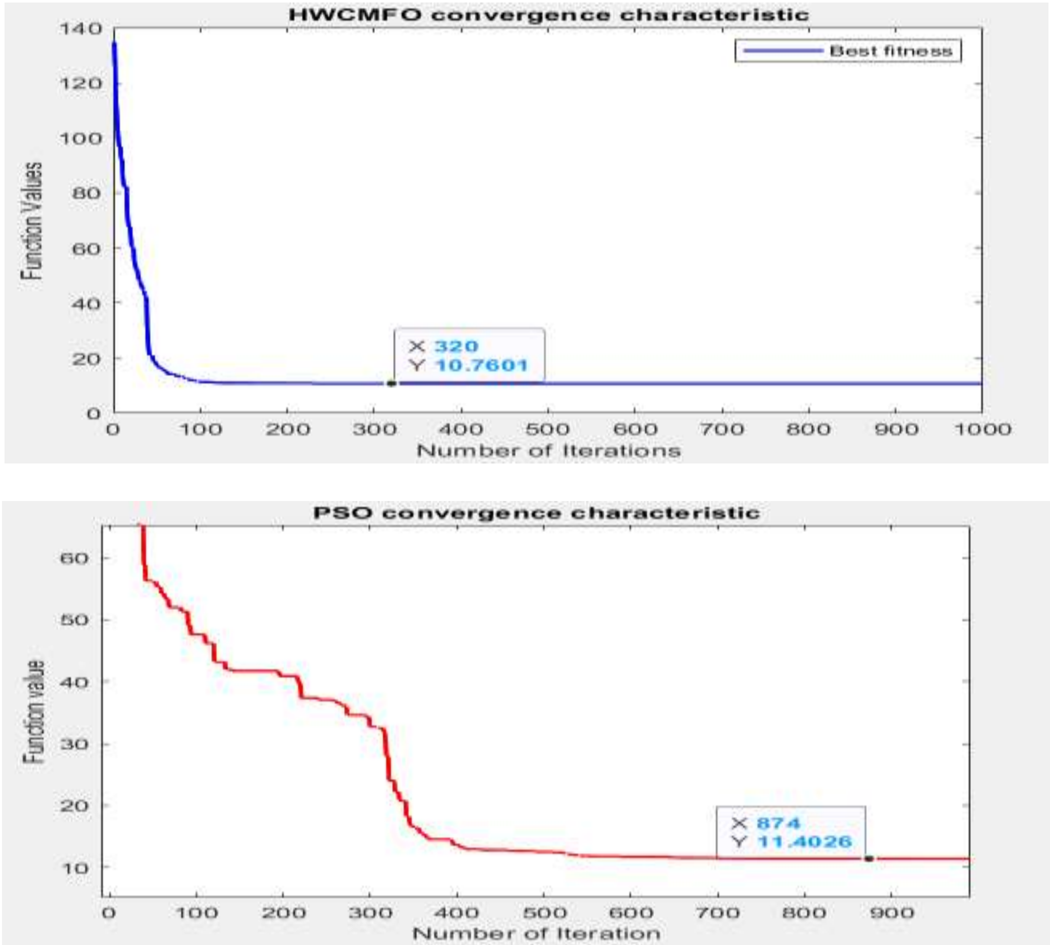


Figure 5.15: Evaluation of the HWCMFO algorithm and PSO algorithm in mode 3

- Evaluation of the HWCMFO algorithm and PSO algorithm in mode 4.

In the last mode (islanding mode), all the DGs in the IEC benchmark operate without the main source. Figure 5.16 shows the best solution of the HWCMFO technique that has been started at around 350th iterations. Besides, it illustrates the biggest iterations of the PSO algorithm among the four modes, which it is obtained the best fitness function value at about 1000 iterations. So, the proposed HWCMFO algorithm has decreased the iterations by approximately three times compared to the PSO algorithm for obtaining the optimal solution.

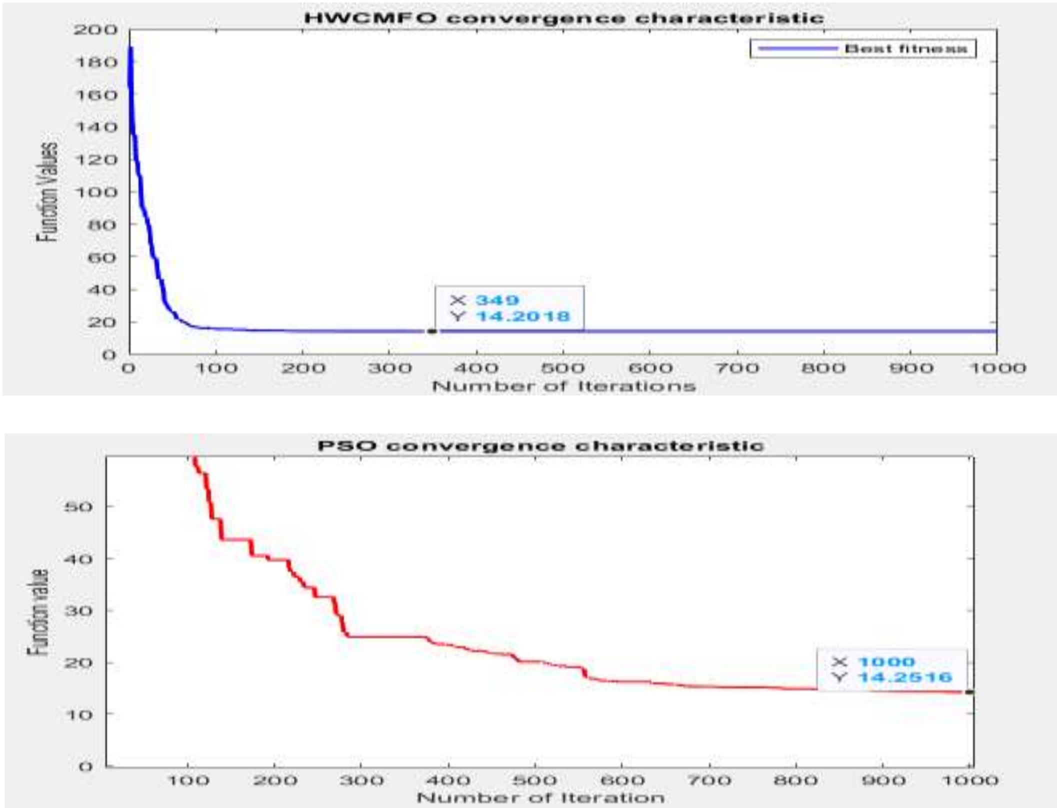


Figure 5.16: Evaluation of the HWCMFO algorithm and PSO algorithm in mode 4

5.6 Summary of the impact of N-SCA on nowadays industrial relays based on a HWCMFO algorithm.

To sum up, when utilizing non-standard proposed characteristics rather than the standard tripping characteristics, the performance of the OCR scheme with the presence of DGs in the DNs will be correctly and reliably adequate due to the suitability of the optimization proposed approach with the characteristics employed within the manufactured industrial relay's. For example, in mode 3, the IEC MG benchmark operates in grid connected mode, which the main utility and four DGs are ON. Due to the integration of the DGs, it can be obvious that most of the fault's values exceeded PSM_{max} as that see in Table 5.8. By applying the proposed N-SCA based on HWCMF technique, the $PSM_{\ new\ max}$ is solved the problem and maintained the reliability by reducing the tripping time by 5.61% and improved the selectivity of the OCR protection system by 6.25% compared to SCA as shown in Figure 5.17. This improvement in relay characteristics is a permissible and easy task due to the simplicity of the programming of nowadays numerical relays and the possibility of creating user-defined tripping characteristics. In addition, the proposed HWCMFO proves its reliability, speed and selectivity for overcurrent protection system when compared to a heuristic optimization technique, namely PSO. It has reduced the operation time, OT and obtained smoothness convergence characteristics for all four abovementioned modes, which gives optimal outcomes with considerably low iterations. Hence proved the proposed HWCMFO algorithm is appropriate to find the global minimum OF value of the OCR coordination. The optimal solution has been obtained just later 78th iteration that is shown by a close observation of characteristics. Then, a computational speed increases due to these few iterations. Moreover, there are no constraints violation has been shown in the convergence characteristics graph.

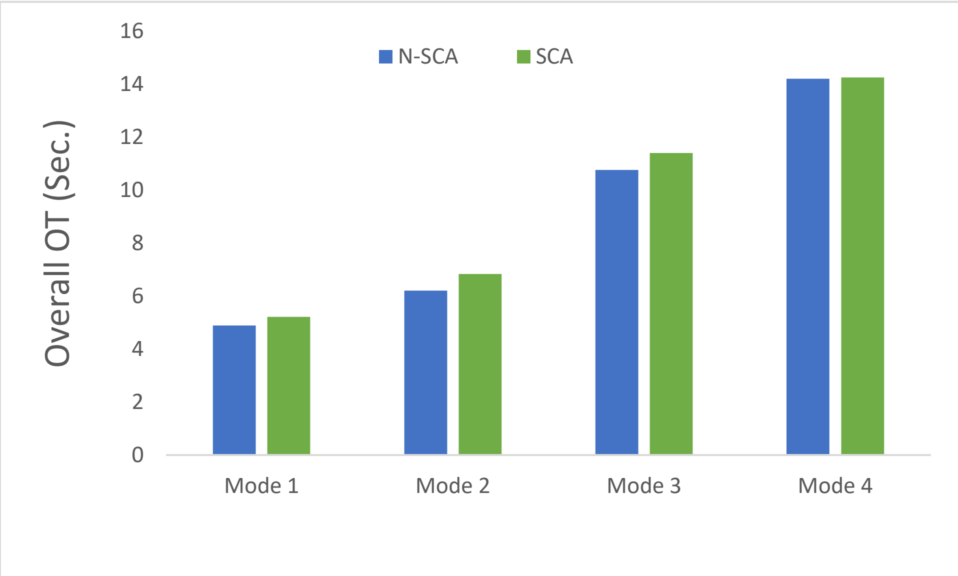


Figure 5.17: The overall OT in N-SCA and SCA for four modes for the radial IEC MG benchmark

Chapter 6: Conclusions and Future Work

6.1 Conclusions of the Present Thesis

This thesis presents an extensive analysis of the overcurrent protection coordination challenges due to the integration of the DGs into the distribution grids. A comprehensive literature review is conducted to evaluate and determine the limitations of present and proposed protection proposals. The protection schemes reported so far in the literature do not address all the design and performance issues of protection to this end simultaneously. Proposing practical and applicable solutions for OCRs coordination problems in DNs with and without DGs is the major purpose of the present thesis. The fundamental contributions and conclusions of the research work displayed in the previous chapters have been provided in this section.

The advantages of replacing conventional overcurrent protection coordination with the optimization methods of overcurrent protection coordination have been highlighted. Particularly, with DGs that integrated into MGs in DNs. Basic requirements of the DNs are increasing the reliability of the system and ensuring the selectivity between the overcurrent protective relays. In this regard, the present thesis introduced two main proposed protection schemes for reaching its goal.

First, the present thesis contributes to find optimal coordination and adaptive approach for OCRs in radial and meshed networks. The novel NSCCT approach has been proposed as a creative non-standard current characteristic that can be utilized in several three phase faults modes of the power networks. It has been represented in Chapter 3 by Equation (3.2). The suggested proposed has been used a logarithmic function and a variable coefficient. The proposed NSCCT technique was investigated and compared with conventional approach and other proposals that recorded in the literature survey under different faults modes. The suggested proposed has been implemented based on standard radial networks, namely IEEE9 bus system and IEC MG benchmark and meshed networks including, IEEE9 and 30 bus system in MATLAP software. It is worth mentioning that the minimum overall operational times, OTs have been obtained by the NSTCC approach compared to standard approach and those reported in the literature for all modes of the abovementioned networks. The optimized value of variable coefficient (A) has illustrated the superiority of the proposed equation due to its flexibility to be appropriate for each mode individually. Specifically, the islanded mode, which is appropriate to detect the minimum fault currents. This is considered to be a key contribution to the suggested proposed, without delay in the optimization task. In addition, utilising only one variable coefficient A in the proposed optimal OCR coordination contributes to reducing the constraints numbers significantly in the coordination as well as the formula of tripping time.

For simulation results for radial networks based on GA of the proposed NSCCT, we can notice that the optimized values of the variable coefficient A for IEC MG are chosen by MATLAB based on the proposed equation as 4.8, 4.8 and 6 for mod1, 2 and 3 respectively. These selected values make the OCRs trip as quick as possible due to its flexibility. The comparison has been done between the proposed method and others who use non-standard IEC curves. For distribution grid without DGs, DN with DGs and islanded mode, the proposed NSCCT is performed of these proposed methods mentioned in literature. NSTCCs reduce the tripping time for the IEC MG benchmark modes 1, 2, and 3 by 42.24%, 60%, and 54.74%, respectively, compared to the lowest OT values reported in literature. Additionally, in the IEEE9-bus radial network, the proposed NSTCCs showed reductions in overall OT for mode 1, mode 2, and mode 3 by 12.06%, 17.33%, and 13.55% compared to STCCs, and by 7.05%, 9.91%, and 11.42% compared to NSS. Within meshed networks using the hybrid GSA–SQP algorithm, NSTCCs enhance the coordination interval time (CTI) between primary and backup relays. The IEEE 9-bus meshed network saw a 16.87% reduction in the sum of CTI values compared to previous literature. The overall OT of the proposed NSTCCs decreased by 78.97% compared to STCC and by 21.33% compared to NSS. In the meshed 30-bus test system, NSTCCs reduced total OT by 54.4% and 37.9% when compared to STCC and NSS, respectively. This NSTCC technique marks a significant advancement in improving the reliability and selectivity of power systems.

Secondly, the thesis presented another unconventional curve for optimum OCRs coordination in DNs with the presence of DGs, it is named N-SCA and represented in Chapter 4, which develops a protection scheme that has been mentioned in the literature review and designed to be proper for various network modes. The concept of the suggested approach is modulating the shape of the standard IEC IN curve of the industrial overcurrent protective relays and extending it to nonstandard PSM times to be in a defined region to be seen by all the OCRs and avoid the miscoordination problem. In the present thesis, the IEC NI characteristics are expanded to 50 PSM to achieve the proposed N-SCA goal. Moreover, a new hybrid optimization technique called HWCMFO algorithm has been proposed in this thesis for solving the proposed coordination problem. It shows that the performance of a numerical protection device and a hybrid optimization technique can be used for exploring the non-standard and user-defined OCR characteristics to ensure adequate coordination of MG protection. For simulation purposes, the radial network IEC MG benchmark is used to test the proposed N-SCA based on the HWCMFO algorithm for acquiring optimal settings for every OCR in different three phase faults modes in MATLAB software. Satisfactory outcomes have been obtained namely minimising the overall operation times, OTs and presenting a suitable CTI between paired primary and backup relays. A NEPLAN package industrial software has been used to apply and test the proposed N-SCA scheme and the conventional approach SCA for evaluating the suggested approach's robustness and effectiveness for the OCRs coordination problem. For comparative purpose, the common heuristic optimization technique PSO is used to evaluate and investigate the proposed HWCMF technique in this thesis. MATLAB software is utilized to test the HWCMFO considering the IEC NI limitation and PSO optimization techniques, the best fitness function values are adopted. The outcomes have been showing the excellence of the HWCMFO algorithm in terms of reliability and speed that it achieved a minimal tripping time, calculated the time of the optimization process rapidly and obtained a few iterations. Furthermore, the results obtained with this hybrid technique are compared with those recorded in the literature survey and with the PSO technique. For all operative modes and among of the others, the minimal tripping time and adequate coordination are achieved by the HWCMFO algorithm with considered the IEC limitations.

The N-SCA surpasses the traditional method across different fault locations within several operational modes. In modes 1, 2, and 3, total OT experiences reductions of 6.32%, 5.61%, and only 0.35%, respectively. For comparison, the PSO method is employed. The HWCMFO technique decreased computing speed by 86.59% for mode 1, 29.69% for mode 2, and 89.18% for islanded mode compared to PSO. Additionally, the HWCMFO method achieves the optimal cost function values faster than the PSO technique across all operational modes. Specifically, reductions for modes 1, 2, and 3 are 74.26%, 63.39%, and 65%, respectively. This indicates that the HWCMFO algorithm effectively determines the global minimum objective function value in OCR coordination.

It can be concluded that these outcomes extended our understanding of the connotation of utilising nonstandard curves in industrial relays for increasing the reliability, and sensitivity of the overcurrent protective relays and ensuring the selectivity between them in the power system.

6.2 Future work

According to the achievement of the present thesis. The research work could continue in this regard and this thesis inspiring to suggest the future work points as follows:

- Testing and validation the proposed techniques in this thesis by utilising on different t fault types such as 1- phase fault, L-L fault and L-G fault. This will provide a more comprehensive understanding of the effectiveness of the proposed protection schemes under various fault scenarios. Additionally, the proposed techniques can be further improved by incorporating machine learning algorithms for real-time fault classification and identification, enhancing the reliability and accuracy of the protection system. Another direction for future work is to investigate the impact of cyber-attacks on the protection system and propose countermeasures to mitigate their effects. Finally, extending the proposed techniques to large-scale distribution systems and integrating RESs, such as wind and solar power, can provide more insights into the challenges of protection coordination in modern distribution network.
- Utilising non- standard characteristics based upon the voltage. This could potentially provide a more accurate protection scheme for DNs with DGs, as the use of standard characteristics may not fully account for the impact of voltage fluctuations caused by the integration of DGs. The effectiveness of non-standard voltage-based characteristics could be tested and compared to traditional characteristics using simulations on different fault types. The utilization of non-standard characteristics based on voltage could potentially lead to improved performance and reliability of protection schemes for distribution grids with DGs.
- Optimal overcurrent relay coordination considering energy not supply (considering reliability). By taking into account the energy aspect, the proposed protection scheme can improve the reliability of the DNs with DGs. The future work will involve developing an optimization algorithm that considers both the energy aspect and OCR coordination in the design of protection schemes. The effectiveness of the proposed protection scheme will be tested and validated on various fault types, including 1-phase fault, L-L fault, and L-G fault, to demonstrate its practical applicability.
- Using hybrid plug setting multiplier instead of a plug setting multiplier that used in Chapter 4. The hybrid plug setting multiplier could potentially offer more optimal coordination of OCRs, leading to increased reliability and sensitivity of the protection scheme. The effectiveness of this approach could be tested and validated through simulation studies on various fault types and network configurations. Additionally, the impact of using hybrid plug setting multiplier on the computational complexity of the optimization algorithm should be investigated to ensure its feasibility for practical implementation in real-world DNs.

- Optimum coordination of OCRs-OCRs and OCRs – voltage restrained overcurrent relays (VROCRs) in DG-connected networks. The integration of DGs into distribution grids has created challenges in protecting networks, especially due to bi-directional current flow. The addition of VROC relays has shown potential to improve protection coordination by preventing unwanted tripping of OCRs during fault conditions. Therefore, an investigation can be conducted to determine the optimal coordination between OCRs and VROC relays in DG-connected networks, which can further enhance the reliability and performance of distribution grids. The proposed techniques can be tested and validated using simulation studies and practical implementation to ensure their effectiveness and applicability in real-world scenario.

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APPENDIX A

IEC MG benchmark data

The base power has been selected as 10 MVA. The details of the studied IEC MG (Kar et al., 2017) are given as follows:

1) Utility: rated short-circuit MVA = 1000, f = 60 Hz, rated kV = 120, Vbase = 120 kV.

2) DGs: 1) DG1, DG3: synchronous generator with rated MVA = 9, f = 60 Hz, rated kV = 2.4, Inertia constant H = 1.07 s., friction factor F = 0.1 pu, Rs = 0.0036 pu, Xd = 1.56 pu, Xd = 0.296 pu,Xd = 0.177 pu, Xq= 1.06 pu, Xq = 0.177 pu, Xl= 0.052 pu, T d = 3.7 s, T d = 0.05 s, Tqo = 0.05 s.

2) DG2: (inverter base DG) Wind farm consisting of three 2 MVA wind turbines (6 MVA, pf = 0.9), f = 60 Hz, rated kV = 575 V, inertia constant H = 0.62 s, friction factor F = 0.1 pu, Rs = 0.006 pu, Xd = 1.305 pu, Xd = 0.296 pu, Xd = 0.252 pu, Xq= 0.474 pu, Xq = 0.243 pu, Xl= 0.18 pu, T do = 4.49 s, T do = 0.0681 s, T q= 0.0513 s. 575 V, 60 Hz.

The synchronous generator with inverter interface to main grid has been considered for the proposed study (Type-4 detailed model in MATLAB/SIMULINK).

3) DG4: DFIG-based wind farm consisting of six 1.5-MVA wind turbines (9 MVA, pf = 0.9), f = 60 Hz, rated kV = 575 V, Inertia constant H = 0.685 s, friction factor F = 0.01 pu, Rs = 0.023 pu, Lls = 0.18 pu, Rr = 0.016 pu, Llr = 0.16 pu, Lm = 2.9 pu.

3) Transformer (TRs): 1) TR1: rated MVA = 15, f = 60 Hz, rated kV = 120/25, Vbase = 25 kV, R1 = 0.00375 pu, X1 = 0.1 pu, Rm = 500 pu, Xm = 500 pu.

2) TR2, TR3: rated MVA = 12, f = 60 Hz, rated kV = 2.4 kV/25 kV, Vbase = 25 kV, R1 = 0.00375 pu, X1 = 0.1 pu, Rm = 500 pu, Xm = 500 pu.

3) TR4: rated MVA = 10, f = 60 Hz, rated kV = 575 V/25 kV, Vbase = 25 kV, R1 = 0.00375 pu, X1 = 0.1 pu, Rm = 500 pu, Xm = 500 pu.

4) Distribution lines (DL): DL1, DL2, DL3, DL4, and DL5: PI-Section, 30 km each, Vbase = 25 kV, R0 = 0.1153 Ω/km, R1 = 0.413 Ω/km, L0 = 1.05 e − 3 H/km, L1 = 3.32 e − 3 H/km, C0 = 11.33 e − 9 F/km, X1 = 5.01 e − 9 F/km.

5) Total loading (sum of L1 to L6) considered: 22 MW, 10 MVAR.

APPENDIX B

IEEE 9 Meshed Distribution Network data

In this system, a mid-point bolted 3ϕ fault is taken for each line, as shown in Figure 3.12, with no backup protection for relays [R17, R19, R21, R23].

Bus 1 is supplied by a power source of 100 MVA and 33 kV with a source impedance of (0 + j0.1) pu.

All DOCRs have the same CTR of 500 : 1.

All these relays are considered to be numerical, in which both PS and TMS are continuous.

In this ORC problem, the lowest acceptable operating time (Tmin) of relays should not be less than 0.2 s.

Load currents of the nine-bus system: Bus 1, Load current (A) —. Bus 2, Load current (A) 350. Bus 3, Load current (A) 100. Bus 4, Load current (A) 100. Bus 5, Load current (A) 350. Bus 6, Load current (A) 350. Bus 7, Load current (A) 350. Bus 8, Load current (A) 100. Bus 9, Load current (A) 10.

APPENDIX C

IEEE 30 Meshed Distribution Network data

Figure 3.13 shows the single-line diagram of the 33 kV part of the IEEE 30-bus network.

The network is sustained by three 50 MVA, 132/33 kV transformers associated with buses 1, 6, and 13.

This test system is modelled as an ORC problem with 86 directional and non-directional OCRs.

Among these 86 relays, a total of 39 DOCRs is considered for the network, which are installed on each end of the lines

For L18, pilot protection is considered.

Two DGs are installed at buses 10 and 15, with transient reactance and capacity of 0.15 p.u. and 10 MVA, respectively.

Two important loads have been located on buses 14 and 3.

The relays (R21, R22) and (R36, R38) are, respectively, placed near generator buses (i.e. bus 10 and bus 15) with high set protections.

The settings of the high set protections of the relays are selected to cover 60% of their lines. The CTR for each OCR is assumed as 500: 1.

For the faults close to CB of relays (R12, R13, R15), the flowing fault currents of relays (R14, R16) are very low, so these two relays cannot be used as backup protection for relays (R12, R15, R16).

APPENDIX D

The HWCMFO Algorithm Pseudo Code

```
Functions: [Lower bound vector (LB), upper bound vector UB, variables numbers (nvars), stream objective function (obj_stream), objective function value ( F_obj), river objective function (obj_ river), sea objective function (obj_sea), river position (pos_river), sea position (pos_sea), calculate the distance between each river or stream and the sea (d) , N_pop, N_sr , d_max, Max it]

Adjust the HWCMFO parameters namely N_pop , N_sr, a and Max it

For i =1: N_pop

    Create a random stream                    In_d (i, :)=LB+(UB-LB). * rand (1, nvars);
    Calculate the stream objective function   obj_In_d (i)=objective_function (In_d (i,:));

End for

Straighten the stream from best to worst based on their objective function value

 Sea - the first stream

 Rivers - N_sr − 1

Stream - N_pop − N_sr

Define the flow intensity for sea and rivers

i = 0;

While   i < Max it

i = i +1;

           Forming Stream

Use spiral movement for updating the stream position

              obj_stream = F_obj of the stream;

          If      obj_stream < obj_ river

                   pos_ river = a new stream

          If          obj_stream < obj_ sea

                        pos_ sea = a new stream

        End if

     End if

    If   obj_river < obj_ sea

          pos_ sea = pos_ river

   End if

 End for

Use spiral movement for updating the rivers position
             obj_river = F_obj of the new river;

      If      obj_river < obj_ sea

                pos_ sea = pos_ river

    End ifEnd for

For streams

Use Levy flight for updating the streams position

   End for

For streams and river

Check the evaporation condition for rivers and streams

        If   d < d_max

          Rain process for both

   End if

End for

Directly reduce the parameter d_max

Directly reduce the parameter a

End while
```

APPENDIX E

Publications:

The majority of the research results provided in this thesis have been published in the following peer-reviewed journals and conferences:

- S. Abeid, Y. Hu, F. Alasali, and N. El-Naily, “Innovative Optimal Nonstandard Tripping Protection Scheme for Radial and Meshed Microgrid Systems,” Energies, vol. 15, no. 14, p. 4980, Jul. 2022, doi: 10.3390/en15144980.
- S. Abeid and Y. Hu, "Overcurrent relays coordination optimisation methods in distribution systems for microgrids: A review," 15th International Conference on Developments in Power System Protection (DPSP 2020), 2020, pp. 1-8, doi: 10.1049/cp.2020.0019.
- S. Abeid, Y. Hu and N. El-Naily, "Optimal overcurrent relay coordination based on hybrid water cycle moth flame optimization (HWCMFO) algorithm considering standard and non-standard characteristics of microgrids," 16th International Conference on Developments in Power System Protection (DPSP 2022), 2022, pp. 433-438, doi: 10.1049/icp.2022.0978.
- N. El Naily, S. M. Saad, S. Abeid, and H. Saleh, "Improved Over-Current Coordination Using Artificial Intelligence In Benghazi MV-Distribution Network Case Study, " 6th International Conference on Engineering & MIS 2020 (ICEMIS'20). Association for Computing Machinery, New York, NY, USA, Article 73, 1–6. https://doi.org/10.1145/3410352.3410809.
- S. M. Saad, S. Abeid, N. e. Naily and H. Y. Mustafa, "Implementation of multi-level coordination scheme to reduce fault clearing time in Libyan distribution system using distance and non-standard overcurrent characteristics," 16th International Conference on Developments in Power System Protection (DPSP 2022), 2022, pp. 189-194, doi: 10.1049/icp.2022.0937.

All the above-mentioned papers and citations are available in Google Scholar and ResearchGate in the links as follows:

- https://scholar.google.com/citations?hl=en
- https://www.researchgate.net/profile/Salima-Abeid

Achievements during the author’s PhD studies:

1- The poster of the paper titled with "Optimal overcurrent relay coordination based on hybrid water cycle moth flame optimization (HWCMFO) algorithm considering standard and non-standard characteristics of microgrids" has been won the best poster prize in the 16th International Conference on Developments in Power System Protection (DPSP 2022).

2- Certificate of achievement for successfully completing the course of "Design course for solar energy system (off-grid, on-grid, protection and simulation" online in June 2022, from Electrical Engineering Portal (EEP) academy.