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Hybrid Tripping Characteristic-Based Protection Coordination Scheme for Photovoltaic Power Systems

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Abstract: Due to the high penetration of renewable energy sources into the electrical power network, overcurrent relays coordination with highly sensitive and selective protection systems are now two of the most important power protection concerns. In this research, an optimal coordination strategy utilising a new hybrid tripping scheme based on current–voltage characteristics has been devised for overcurrent relays in a power network coupled to a photovoltaic system. This research develops and proves a new optimal coordination scheme based on two optimisation methods, the vibrating particles system and particle swarm optimisation algorithms, in consideration of the impact of renewable sources on fault characteristics. The new optimal coordination approach aims to improve the sensitivity and dependability of the protection system by reducing the tripping time of the overcurrent relays by employing a new hybrid tripping scheme. A specific case study, Conseil International des Grands Réseaux Electriques (CIGRE) distribution network connected to two photovoltaic systems is constructed and presented utilising Industrial software (namely ETAP), and the outcomes of the proposed optimal coordination scheme are compared with standard and recent characteristics from the literature. The hybrid tripping scheme and optimisation techniques are evaluated using different fault and power network model scenarios. The results show that the optimal hybrid tripping scheme provided successfully decreases the overall operating time of the overcurrent relays and increases the sensitivity of the relay during all fault scenarios. The reduction in overall time for the proposed hybrid tripping scheme was 35% compared to the literature for the scenario of a power grid with and without photovoltaic systems.

Keywords: overcurrent relays; optimal coordination; renewable energy; nonstandard tripping characteristics

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1. Introduction

Photovoltaic (PV) arrays, wind turbines, and fuel cells are all examples of Distributed Generators (DGs) that can be integrated into an existing Distribution Network (DN) to save energy costs, improve reliability, and satisfy environmental regulations. Furthermore, utilities benefit from higher power quality with such DG systems in place. However, DGs cause a change in the level and characteristics of the fault current and bidirectional power flow [1–3]. As a result, the conventional method of protecting DN with DGs based on the use of Overcurrent Relays (OCRs) is becoming more challenging. In addition, when designing a protective system to deal with varying fault levels and different grid operation modes (with and without DG), the DN's ability to operate in these modes is an important concept to take into account [4]. Redesigning or replacing the protection system in a DN due to the integration of the DGs can be costly and technically challenging. By increasing the capacity of DG penetration in DN, the OCR settings must be modified to cope with the changing power flow and fault. Adaptive protection systems in radial DNs often adjust the relay settings according to the role of the communication system. However, in many DNs, establishing a communication infrastructure for power protection systems may be an expensive choice. The recent and main OCR coordination approaches for DN with DG are divided into six categories, which are shown in Figure 1, as follows [4,5]:

- Developing a new objective function to address the OCR coordination problem.
- Applying and developing a dual-setting approach in OCR.
- Designing and developing a non-standard characteristic for OCR.
- Using a new optimisation algorithm to solve the complex OCR coordination problem for a DN with DG.
- Applying and developing new constraints to the objective function.
- Designing and developing a hybrid tripping characteristic for OCR.

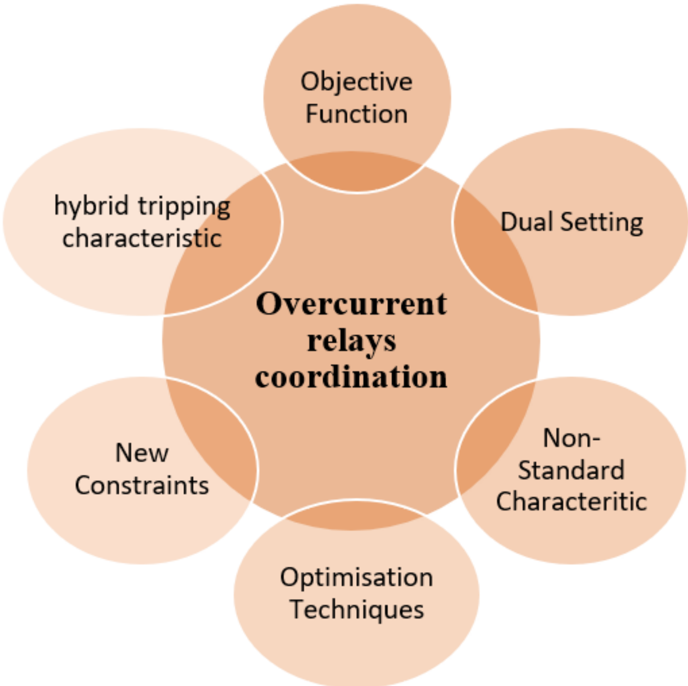

Figure 1. The recent and major OCR coordination approaches for DN with DGs.

The primary purpose of all of the aforementioned approaches is to obtain the appropriate setting for protection schemes to maintain the reliability of protection scheme performance for interconnected DNs with DGs. Therefore, this research presents a new non-standard current–voltage characteristic for programmable OCRs as a hybrid tripping characteristic approach. The magnitudes of the faulty phase voltage and current are used by the suggested method to calculate the relay's operation time by employing a new optimisation method. Plus, it can safeguard DNs with extensive penetration of DGs in the grid-connected mode of DN operation, and it does not rely on any sort of communication infrastructure. Academics and industry professionals have focused significantly on the problem of DN protection due to the stochastic behaviour of DGs. Several approaches have been proposed to provide an adequate method of protecting the microgrid in both modes (with and without DGs). Some of them concentrate on communication channel protection [6,7]. Slemaisar-doo et al. [8] suggested a differential protection approach employing a non-nominal frequency-current during a microgrid fault that is superior to traditional overcurrent protection in detecting the microgrid fault. Aghdam et al. [9] proposed a differential protection method based on variable tripping times, and a multiagent protection scheme was designed to improve the coordination of adjacent relays. Communication-based strategies are realistic microgrid protection options. However, the reliability of this type of protection highly depends on the communication facilities and performance; it is also not an economically viable solution. In addition [6,10], these schemes are affected by a communication failure, imbalanced loads, and transients' events during the connection and disconnection of DGs. These days, it is common practice to employ programmable relays (microprocessor relays) to apply non-standard characteristics. The literature proposed several concepts, including a logarithm characteristic for OCRs [5,10], a combination of standard characteristics and a non-standard term based on voltage [5], and a standard characteristic under new constants [5,10] for DNs with DG to reduce the total amount of time spent operating the OCR. However, these approaches are utilised in radial DNs with DG, and all of these techniques require a communication infrastructure. Therefore, the purpose of this study is to introduce a new hybrid optimal coordination strategy that does not require a communication link between the OCRs. This is intended to reduce the demand for communications infrastructure while improving the coordination approach of the OCR. Furthermore, the suggested method will reduce computing costs and the necessity to access voluminous PV and network data.

Because of phase OCR's inapplicability for handling the complexity of DN-integrated PV systems, the voltage term is being explored as a potential term for solving the OCRs coordination issue [11]. In [12], a voltage-restricted overcurrent relay is presented using phase voltage and current to set the necessary threshold. Nevertheless, the PV plant's control method may cause phase currents to be larger in a healthy phase than in a faulty phase, leading to the relay in miscoordination events. Few studies have looked into the use of voltage terms in the OCRs coordination problem [13]. The use of voltage-restricted OCRs coordination schemes for network protection was discussed, for example, in [14]. However, no voltage limitation was presented with the OCR algorithm or result [14]. The voltage–current–time inverse model presented by Singh et al. [15] is based on variations in currents and voltages during fault events. The suggested OCR coordination model improves operating time and maintains protection coordination for power networks with PV systems without considering different modes of the grid. El-Sayed et al. [16] introduced a current–voltage scheme for directional OCR based on measuring harmonic currents and voltages at the relay position to guarantee optimal protection coordination for the islanded microgrid without taking into account bidirectional power flow and grid-connected operation mode. Protection schemes that use conventional inverse time–current characteristics are becoming increasingly unsuitable as the penetration of DGs in the DN rises. Authors [17,18] presented a voltage-based protection scheme to minimise the operating time of the relay compared to the traditional inverse time current scheme. Another study [19] proposes a strategy for protecting the DN using the superconducting fault limiter based on the voltage parameter. There is a limited number of research that used the non-standard logarithmic function for developing a current–voltage protection coordination scheme for DN with DGs under different grid operation modes and fault scenarios.

The foregoing challenges and evidence point to the necessity of having a flexible protection mechanism for more dynamic power networks with DG in the future. OCR protection schemes must be compatible with dynamic power systems in terms of their ability to overcome and accommodate these emerging features, raising questions about the appropriateness of standard characteristics of OCR protection schemes, stability, and protection selectivity for DN with DG. In this paper, we introduce a novel hybrid tripping scheme based on non-standard current–voltage characteristics for fast response OCR prevention in DNs with PV farm systems without using a communication protocol. The following are some of the study's contributions that aim to bridge this research area gap:

1. To enhance the performance of the protection system, a new non-standard logarithmic and hybrid tripping coordination scheme based on current–voltage characteristics is established for DN with DGs. In this article, a significant reduction in total operational time is achieved, with no instances of miscoordination compared to typical

characteristics of the OCR scheme. This work compares the proposed new hybrid tripping OCR scheme (HOC) with the common inverse time–current characteristic (SIC) and the time–current–voltage characteristic (CVC) from the literature [16,20].

2. In the literature [20], the use of modern optimisation techniques in solving protection problems, such as the particle swarm algorithm [21,22] assists in achieving the optimal OCR settings. To solve the OCR coordination problem based on the non-standard current–voltage characteristic and reduce the total operational time of OCRs, a new optimisation technique, the Vibrating Particles System (VPS) approach, has been designed and employed.
3. Since the proposed hybrid optimal coordination scheme in this work only uses locally obtained measurements, no medium of communication between the OCRs is necessary. This eliminates the demand for communications infrastructure and reduces computational costs and the requirement for access to extensive PV and network data.
4. The sensitivity and selectivity of the proposed hybrid optimal coordination scheme have been investigated for DN (benchmark power network, CIGRE) with DGs under different fault scenarios and operation modes. This aims to provide network operators with a preliminary indicator regarding the potential impact of DGs on the fault contribution and relay setting.

The following sections are ordered as follows: The optimum OCRs coordination problem formulation is introduced in Section 2. In addition, the proposed hybrid tripping scheme is developed. The results and comparison are discussed in Section 3. In Section 4, the summary and conclusion of this work are presented.

2. Problem Formulation of Optimum OCRs Coordination

The coordination problem of OCRs in a DN with DGs can be formulated as an optimisation problem [1,5]. This formulation's purpose is to identify the OCRs settings that reduce the overall operational times of OCRs without sacrificing the selectivity between primary and backup relays. Figure 2 describes the structure and workflow taken in this paper.

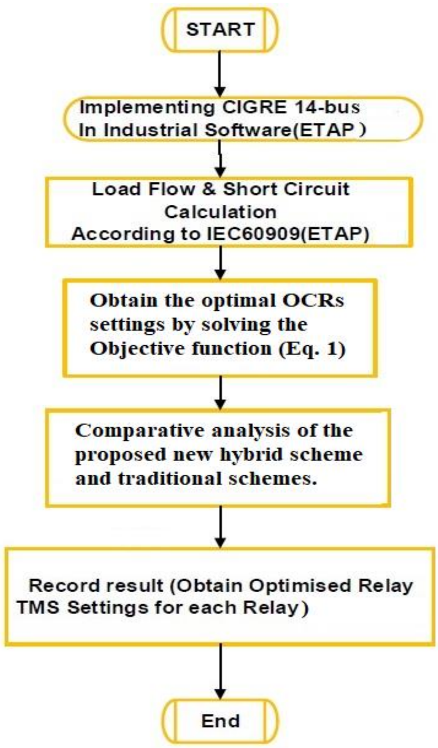

Figure 2. The structure and general workflow for optimum OCRs coordination.

This section offers a mathematical formulation of the proposed optimisation approach to solve the coordination problem and enhance the performance of the optimisation strategies for OCRs. The objective function (OT) is, therefore, utilised to minimise the overall operating time of the primary and backup OCRs. OT can be expressed as described in Equation (1) [1,5].

$$\mathrm{OT} = \sum_{r=1}^{R}\sum_{f=1}^{F} t_{r,f} \tag{1}$$

where $t_{r,f}$ is the operational time of the relay, r, at the fault location, f. R is the number of OCRs and F is the total location of the fault in the DN. The objective function, OT, is subject to the following constraints.

2.1. Selectivity Constraints

The objective of the selectivity or coordination restriction is to extend the lag time between the primary and backup OCRs in terms of propositional operations. This producer will help in reducing the impact of a power loss on the network by pinpointing the precise location of the defect; in this case, the backup OCRs should be inoperable unless the primary OCRs fail to do so. As a collection of inequality constraints, selectivity and coordination criteria can be stated using the Coordination Time Interval (CTI) [1,4].

$$t_{\mathrm{backup}} - t_{\mathrm{primary}} \geq \mathrm{CTI} \tag{2}$$

where the t_{primary} is the operational time for the primary OCR and t_{backup} is the operational time of the backup OCR. The CTI value is based on several criteria, including relay type and circuit breaker speed. To achieve selectivity, the CTI is often set between 0.2 and 0.5 s according to IEEE-242. Therefore, the CTI is equal to 0.3 in this study, similar to [1,4].

2.2. Relay Settings Constraints

To preserve the OCRs operational time constraints, minimum and maximum OCR operational time requirements must be presented. However, protective relays should run with the shortest operational time possible; if they take longer to work, equipment damage and power system instability will result. Here are the minimum and maximum operational time limits:

$$t_{min} \leq t_r \leq t_{max} \tag{3}$$

$$TMS_{min} \leq TMS_r \leq TMS_{max} \tag{4}$$

where t_{min} and t_{max} are the minimum and maximum OCR operational time, t_r is the operational time of the relay r. TMS_{min} and TMS_{max} are the minimum and maximum Time Multiplier Settings (TMS). TMS_r is the TMS value for relay r. In this study, TMS is handled as a continuous variable, and OCRs need to work within the operating period of the protection schemes. Therefore, the TMS should be set within the maximum and minimum values under different fault conditions, or even during a light overload. TMS limits range from 0.01 to 3 [5], and the TMS for the majority of industrial and microgrid OCRs falling within this range.

2.3. Characteristics of the Relay

In general, the operation time of an overcurrent relay (OCR), t, is dictated by a standard inverse function of the fault current and operational time. The characteristic equation governing the relay's working time varies based on the OCR's manufacturer and type of the relay. In this paper, standard OCRs are employed in conjunction with the IEC255-3 standard characteristic equation as described in (5) as a reference scheme to compare our proposed scheme with it [4,5].

$$t = \left[\frac{A}{\left(\frac{I_f}{I_{pi}}\right)^B - 1} \right] TMS \tag{5}$$

where I_f is the fault current, I_{pi} is the pickup current, A and B are constants defined based on the OCR standard such as IEEE, IEC, and AREVA. Numerical and programmable relays, such as OCRs (microprocessor relays), can typically have their time-operating properties modified and updated via a network connection and real-time data. In this article, the numerical relay (OCR) is used in this article based on industry standard (IEC) where A and B are equal to 014 and 0.02, respectively [2,5]. The normal standard inverse time-current characteristic is shown in Figure 3 for the relation between operational time, t, and $\frac{I_f}{I_{pi}}$.

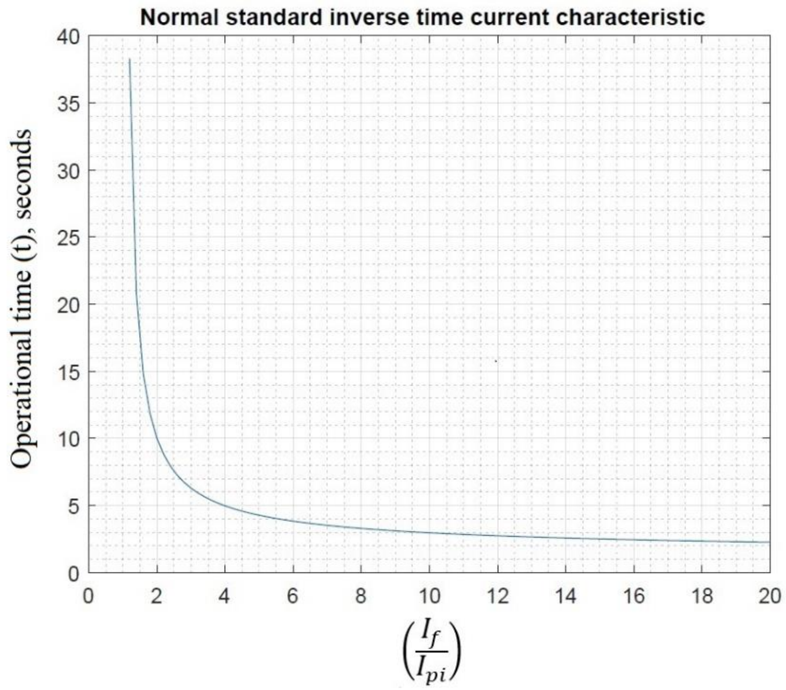

Figure 3. The normal standard inverse time–current characteristic for the OCR.

In addition to the standard inverse characteristic, in [23] a time–current–voltage characteristic for OCR based on the phase fault voltage, V, is proposed as follows:

$$t = \left(\frac{1}{e^{1-V}}\right)^K TMS \left(\frac{A}{\left(\frac{I_f}{I_{pi}}\right)^B - 1} \right) \tag{6}$$

The time–current–voltage characteristic of [19], as described in Equation (6) and shown in Figure 4, is also used as a reference OCR scheme, which will be compared to the hybrid tripping scheme in this work.

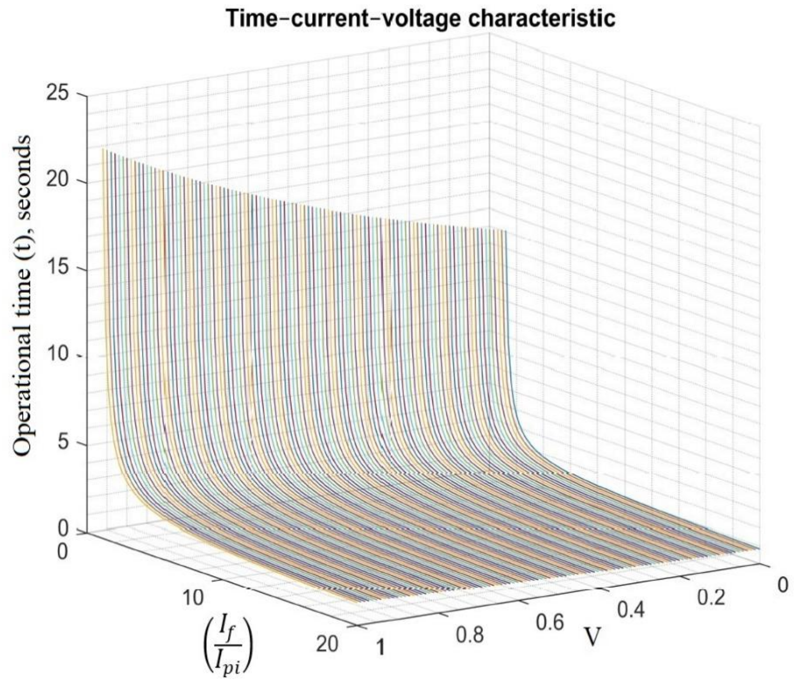

Figure 4. Time–current–voltage characteristic for OCR.

2.4. Proposed Hybrid Tripping OCR Characteristic

In the literature, the typically inverse time–current characteristic [1,2] and time–current–voltage characteristic [23] are restricted to certain values of the setting of low and high multipliers. As previously explained, the fault characteristics of a power system network incorporating renewable energy sources are challenging and distinct. The limitation of using characteristics from the literature reduces OCR's sensitivity in the event of maximum and minimum fault currents at different operation modes for the DN [5]. This work proposes an advanced hybrid OCRs characteristic and coordination approach based on a non-standard current–voltage characteristic based on a logarithmic function to alleviate the limitations in the standard characteristics and the protection difficulties for DG systems. Furthermore, the tripping characteristics of OCRs as described in Equations (5) and (6) [5] are significantly longer for DGs with a weak fault infeed, making them unsuitable for use in power networks with low fault currents. This limitation is alleviated in this work by the introduction of a new hybrid tripping OCR characteristic based on a logarithmic function for the currents $(\frac{I_f}{I_{pi}})$ and the phase voltage (V_P). The new hybrid tripping OCR characteristic is presented in Equation (7):

$$t = \left(5.8 - 1.35 * \log_e\left(\frac{I_f}{I_{pi}}\right)\right) \log_e(9V_P + 1)\ TMS \tag{7}$$

To achieve selectivity in OCR coordination, the grading time must be independent of the network fault location and fault current level. Equation (7) presents the proposed hybrid tripping OCR characteristic utilizing logarithmic and constant coefficients for all relays. This helps the classification time to be independent of the fault level and location. To establish the best *TMS* in Equation (7) that minimises the operation tripping time, the next section describes the optimisation algorithm that has been used to find the optimal OCR setting and *TMS*. Figure 5 presents the current–voltage characteristic curve based on a logarithmic function.

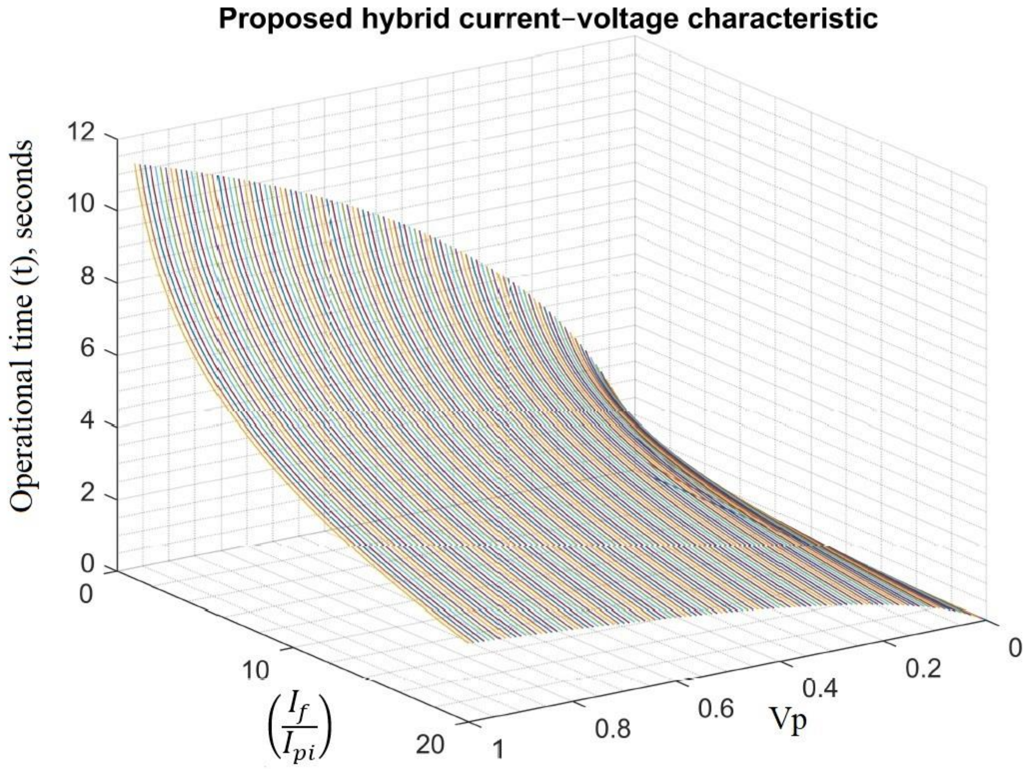

Figure 5. Proposed hybrid current–voltage characteristic for OCR.

2.5. Optimisation Methods for Solving the OCRs Coordination Problem

In this section, the OCRs coordination problem represented by Equation (1) for a DN with connected DGs is treated as an optimisation problem. This section presents two optimisation algorithms, Particle Swarm Optimisation (PSO) and the Vibrating Particle System (VPS) approach, as common and new powerful optimisation algorithms for solving OCR coordination problems using the standard inverse time–current characteristic [2,4], the time–current–voltage characteristic [20,23], and the hybrid current–voltage characteristic.

2.5.1. PSO Algorithm

This research introduces and employs the PSO algorithm, as depicted in Figure 6 [24,25], as a common optimisation technique to solve OCR coordination problems. Kennedy and Eberhart established PSO as one of the most effective approaches for solving complex engineering optimisation problems [2,26]. Furthermore, the PSO is a cutting-edge heuristic optimisation technique, and its inherent simplicity means that it uses fewer CPU resources. Consequently, the PSO's global solution finding, rapid convergence, and easy implementation have made it popular in a variety of contexts, including energy, power flow, and protection system problems [5,26]. Based on the benefits of this strategy, the PSO method is used here to provide a common and reference algorithm for solving the proposed coordination problem, as described in Equation (1). In general, PSO mimics and is inspired by human social behaviour and the behaviour of swarming animals [5]. The objective of the PSO algorithm is to maintain and govern the population of agents or particles (called a "swarm"), where each swarm of particles represents a potential solution. In PSO, the population of the swarm represents the solution, and each particle represents an individual result. The particles memorize their current and optimal population position relative to the objective function under consideration (Equation (1)). The trajectory of the particles will be modified based on their position and the optimal position of the swarm. In each iteration, improved placements and optimal solutions are discovered, which influence particle movement in the swarms. Each particle moves inside the search space with a variable velocity. In the end, the PSO model will identify the optimal answer among all conceivable alternatives, which is known as the "global solution".

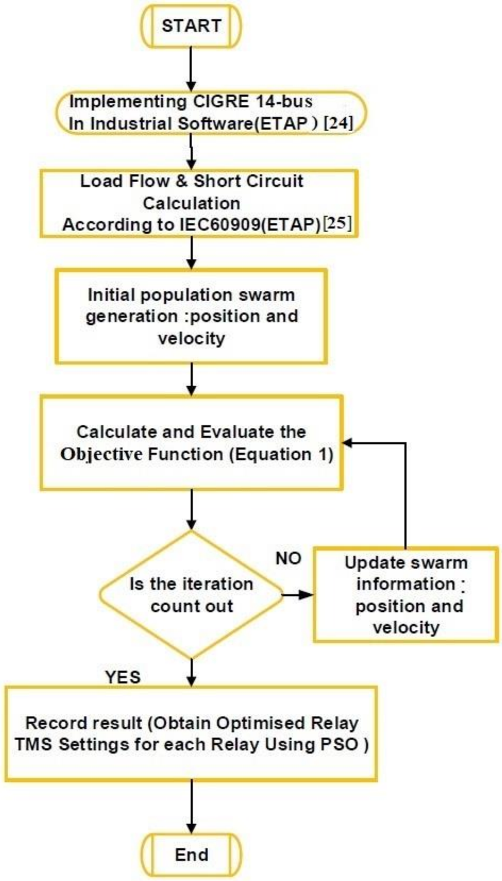

Figure 6. Outline of the optimisation technique (PSO) for solving the OCRs coordination problem [24,25].

Figure 5 depicts the outline of the optimisation technique for the proposed coordination of OCRs problem. First, using the measured network information, load flow and short circuits are computed. Then, the PSO model is used to generate an initial swarm population based on all of the input data. In this article, we describe the PSO optimisation model through the minimal cost function, Equation (1), and the protection and network constraints, Equations (2) to (4). After the swarm's data have been updated, the process will repeat itself based on the fitness values of the goal function. Finally, the OCRs problem's global solution will be found by the PSO model at the end of each iteration, and the TMS will be determined as a result.

2.5.2. VPS Algorithm

In 2017, an evolutionary metaheuristic search strategy, the Vibrating Particles System (VPS) approach [27], was created by Kaveh and Ilchi Ghazaan. It encourages natural vibration of systems with a single degree of freedom subject to viscous damping. VPS has been used to solve a variety of structural and engineering optimisation problems, with positive results in terms of convergence and accuracy [28]. The newly presented optimisation algorithm (VPS) is intended to tackle complicated optimisation problems with minimal computational effort and expense. Therefore, the proposed VPS algorithm can be an extremely efficient and potent algorithm to tackle complex protection coordination problems for a power network with integrated DGs. Similarly, to other population-based metaheuristics, VPS starts with a random pool of initial solutions and analyses them as single degrees of freedom in vibrating systems. When a freely vibrating system is subjected to damping conditions, it oscillates and eventually finds its equilibrium position according to a predetermined formula. Differential equations are used to easily demonstrate this case. VPS improves the quality of the particles on a regular basis during the optimisation process by oscillating them forward to the equilibrium position using a combination of randomness and exploitation of the data collected [27,28]. Consider that the equilibrium position of each particle includes three parts: the highest optimal position (HOP), a good optimal particle (GOP), and a bad optimal particle (BOP). Therefore, there are essentially three concepts for the movement towards the global optimal solution:

1. Self-adaptation: In a process of self-adaptation, the particle shifts its trajectory to approach HOP.
2. Collaborations: The new particle's location can be influenced by the GOP and BOP.
3. Competitions: In terms of competition, GOP is more influential than BOP.

For each particle, VPS modifies the weights in HP, GP, and BP. Following a population-level application of a penalised objective function sort, values are then ranked in ascending order. Both the GOP and the BOP for a given particle are drawn at random from the first and second halves of the population, respectively. Good particles, bad particles, and the algorithm's best particle up to this point are compared using different constant weights, and the rand is a uniformly produced random number between 0 and 1. It should be mentioned that VPS adjusts the location of particles using memory based on the harmony search approach [27]. The best solution (TMS) will be chosen at the end of the iteration process, when the number of objective function evaluation iterations (NFEs) exceeds the maximum number of NEFs (maxNFES), as shown in Figure 7.

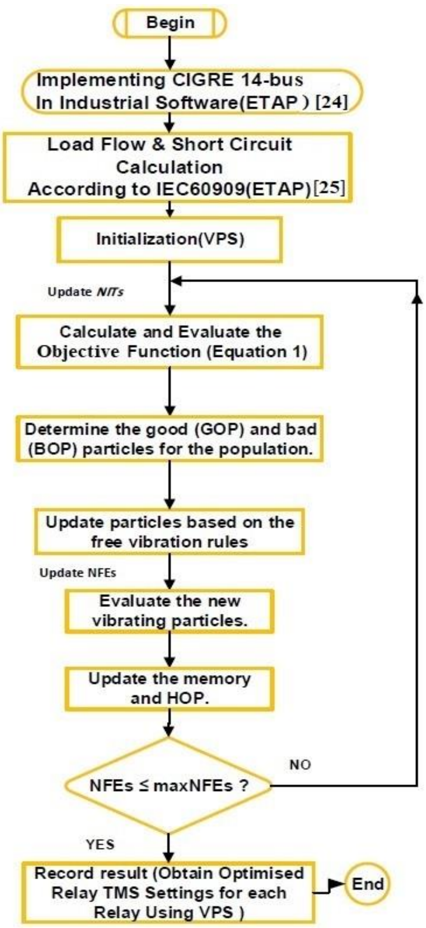

Figure 7. Outline of the optimisation technique (VPS) for solving the OCRs coordination problem [24,25].

3. Results

The formulation described in Section 2 for the OCRs coordination problem is evaluated using a CIGRE distribution network as a common and standard DN. Figure 7 shows the CIGRE distribution network, and a detailed description of the CIGRE grid is discussed in [29]. The proposed hybrid tripping OCR scheme suggested in this paper was first applied to protect the CIGRE network with or without DGs (two PV systems). This section will describe the results of the hybrid tripping OCR characteristic provided under different network operation modes (with and without DG) and different fault scenarios. Furthermore, this section compares the proposed hybrid tripping OCR scheme (HOC) to the common inverse time–current characteristic (SIC) and time–current–voltage characteristic (CVC) [20,23]. Presented is a comparison of the total operational time for HOC, SIC, and CVC in several power network scenarios. Using the three tripping characteristics, the VPS and PSO optimisation algorithms are applied to solve the OCR protection coordination problem. The outcomes of both the VPS and PSO models are also evaluated and contrasted. The HOC approach has been evaluated using industrial software (ETAP), and the findings are provided and compared to the SIC and CVC schemes.

3.1. Description of the CIGRE Distribution Network under Study

The proposed HOC scheme is tested on a CIGRE distribution network, as shown in Figure 8, to determine optimal OCRs coordination and achieve the minimum tripping time. The CIGRE grid is developed based on a 14-bus feeder, and all details are described in [29]. In general, the CIGRE grid is fed by a utility HV/M source and protected by 12 OCRs. Furthermore, this grid is connected to two PV units (each rated at 5MVA) through a 1/20 kV set-up transformer, as described in more detail in [2,5]. On each line, three-phase faults are done at nodes (F1–F12) that represent the near-end and far-end fault locations. Each fault location is assigned two primary OCRs, with one backup OCR for each primary OCR. The Plug Setting (PS), pickup current (I_{pi}), and Current Transformer Ratio (CTR) for each OCR are displayed in Table 1. The load flow was generated to determine the CTR and PS for each OCR initially. In addition, a three-phase short-current determine according to IEC-60909 for different locations. Consequently, the HOC, SIC, and CVC schemes utilised in this investigation have been detailed. The three-phase short-circuit was examined using the ETAP software and the relevant data. The OCR data required to simulate the power network model are listed in Table 1.

Table 1. The PS, I_{pi}, and CTR for each OCR.

Relay	**CTR**	**PS**	I_{pi}**(A)**
HOC1	200/1	60	120
HOC2	200/1	60	120
HOC3	100/1	50	50
HOC4	100/1	50	50
HOC5	100/1	20	20
HOC6	100/1	20	20
HOC7	100/1	60	60
HOC8	100/1	50	50
HOC9	100/1	30	30
HOC10	100/1	20	20
HOC11	100/1	30	30
HOC12	100/1	50	50

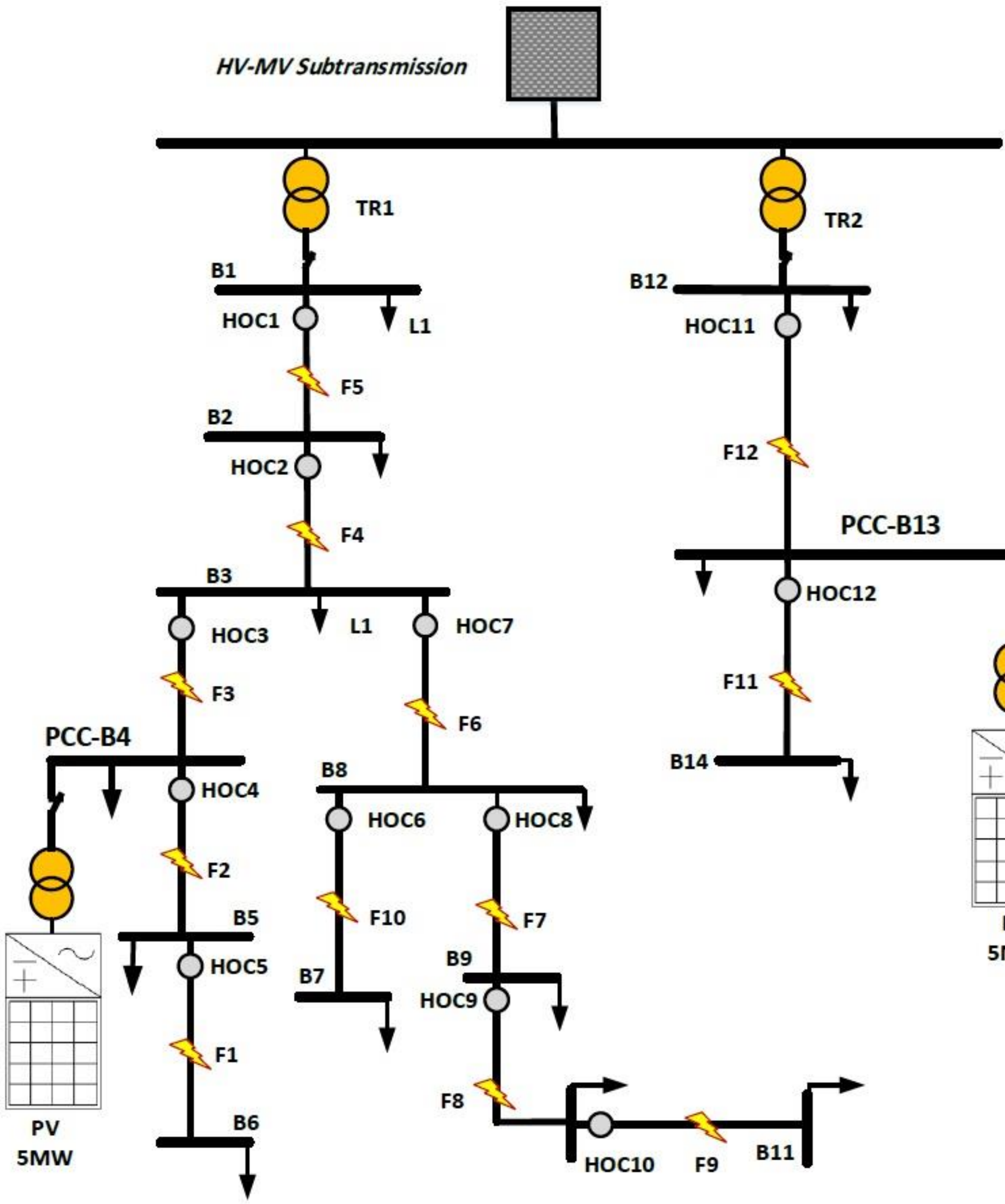

Figure 8. CIGRE distribution network.

3.2. Test Results for CIGRE Distribution Network without PVs

To demonstrate the performance advantage of the proposed hybrid tripping scheme (HOC) in terms of providing the shortest tripping time while preserving suitable CTI across OCR pairs, Table 1 displays the tripping times of all OCR pairs (primary and backup) at various fault sites for the distribution network without PVs. In addition, Table 2 displays the number of recorded delays in trip time when the SIC and CVC approaches were employed in comparison to the HOC approach. For instance, 0.27 s in comparison to 0.59 and 0.56 s for OCR 4 when utilizing the HOC compared to SIC and CVC, respectively, in the event of a three-phase fault at F3.

Table 2. The operating time values in seconds (S.) of OCR for the SIC, CVC, and HOC approaches for the CIGRE distribution network without PVs.

Fault	Fault Current (A)	OCR	SIC (S.)	CVC (S.)	HOC (S.)
F1	1223.0	5	0.02	0.01	0.00
	1223.0	4	0.32	0.31	0.31
F2	1415.0	4	0.31	0.26	0.12
	1415.0	3	0.61	0.56	0.42
F3	1500.0	3	0.59	0.52	0.27
	1500.0	2	0.89	0.82	0.57
F4	1603.0	2	0.87	0.77	0.54
	1603.0	1	1.17	1.07	0.84
F5	3239.0	1	0.91	0.69	0.54
	3239.0	—	0.00	0.01	0.00
F6	1394.0	7	0.90	0.89	0.40
	1394.0	2	0.92	0.87	0.60
F7	1352.0	8	0.60	0.52	0.15
	1352.0	7	1.00	0.94	0.46
F8	1258.0	9	0.32	0.29	0.21
	1258.0	8	0.61	0.59	0.51
F9	1205.0	10	0.02	0.01	0.00
	1205.0	9	0.32	0.31	0.30
F10	1195.0	6	0.03	0.01	0.01
	1195.0	7	0.98	1.01	0.60
F11	2039.0	11	0.02	0.01	0.005
	2039.0	12	0.32	0.54	0.48
F12	2943.0	12	0.29	0.45	0.34
	2943.0	—	0.02	0.00	0.00

Observably, the HOC approach reduces the trip time of all OCRs compared to the SIC and CVC approaches. The use of the HOC method as mentioned in Table 2 reveals the tendency of all OCRs to create an exact CTI among all fault conditions. In addition, the OCR times satisfy all optimisation constraints when the HOC approach is applied. As shown in Table 2, the sensitivity task is adequately provided using the HOC, demonstrating the superiority of the suggested method.

3.3. Test Results for CIGRE Distribution Network with PVs

To evaluate the effects of the novel HOC approach, the ideal OCR configuration for the CIGRE distribution network fed by a utility feeder and two PV systems was found, as illustrated in Figure 7. Table 3 displays the trip time for the primary and backup OCR pairs for three-phase faults for the HOC, SIC, and CVC characteristics under grid-connected PV mode. The HOC strategy outperforms both the standard OCRs method (SIC) and CVC. The operational time of all OCRs, as provided in Table 3, indicates that the HOC decreased with the maintaining of sufficient CTI between primary and backup OCR pairs, as compared to SIC and CVC approaches. For example, the HOC approach achieved a trip time of 0.535 s for OCR 2 during F4, while the SIC and CVC approach achieved times of 0.894 and 0.817 s, respectively. By decreasing the time it takes for relays to trip, the HOC technique has the potential to shorten the amount of time relays need to be in operation, which in turn would improve the reliability of the power grid.

Table 3. The operating time values in seconds (S.) of OCR for the SIC, CVC and HOC approaches for the CIGRE distribution network with PVs.

Fault	Fault Current (A)	OCR	SIC (S.)	CVC (S.)	HOC (S.)
F1	1223.0	5	0.021	0.009	0.004
	1223.0	4	0.322	0.309	0.305
F2	1415.0	4	0.309	0.259	0.102
	1415.0	3	0.604	0.554	0.411
F3	1500.0	3	0.593	0.518	0.249
	1500.0	2	0.894	0.817	0.564
F4	1603.0	2	0.871	0.772	0.535
	1603.0	1	1.171	1.072	0.820
F5	3239.0	1	0.914	0.692	0.533
	3239.0	—	0.000	0.000	0.000
F6	1394.0	7	0.898	0.796	0.406
	1394.0	2	0.925	0.868	0.599
F7	1352.0	8	1.610	0.519	0.192
	1352.0	7	0.904	0.821	0.466
F8	1258.0	9	0.317	0.293	0.213
	1258.0	8	1.647	0.593	0.516
F9	1205.0	10	0.021	0.008	0.002
	1205.0	9	0.321	0.310	0.300
F10	1195.0	6	0.029	0.013	0.006
	1195.0	7	0.886	0.899	0.610
F11	2039.0	11	0.018	0.009	0.005
	2039.0	12	0.318	0.541	0.476
F12	2943.0	12	0.292	0.449	0.347
	2943.0	—	0.000	0.000	0.000

3.4. Discussion and Comparison

This section contrasts the efficiency of the suggested HOC approach compared to traditional SIC and CVC strategies in the two power grid scenarios (with and without PV). In general, Table 4 displays the overall OCRs' tripping times for the two power grid scenarios. The TMS and overall operational time in each power grid scenario are reported in Table 4 and were computed using the VPS optimisation technique. To analyse the effectiveness of these acquired settings in terms of total operational time and CTI, we used ETAP software to simulate fault scenarios and then investigated their performance using HOC, SIC, and CVC techniques. In Table 4, we can see that the comparison results in shorter operating times for all OCRs in all cases. The overall operational times for the power grid connected to PVs were 11.86, 11.14, and 7.68 s for the SIC, CVC, and HOC approaches, respectively. Furthermore, the reduction in the overall time for HOC was 35.3% and 33% compared to SIC and CVC, respectively, for the scenario of a power grid without PV.

Table 4. The overall operating time in seconds (S.) and TMS values of OCRs for the SIC, CVC, and HOC approaches for the CIGRE distribution network with and without PVs.

OCR	**Without PVs**			**With PVs**		
	TMS					
	SIC	**CVC**	**HOC**	**SIC**	**CVC**	**HOC**
1	0.445	0.464	0.597	0.445	0.464	0.584
2	0.330	0.465	0.474	0.331	0.465	0.472
3	0.299	0.666	1.28	0.298	0.66	1.19
4	0.151	0.328	0.62	0.155	0.328	0.524
5	0.01	0.01	0.01	0.01	0.01	0.01
6	0.01	0.01	0.01	0.01	0.01	0.01
7	0.416	0.977	0.995	0.424	0.873	1
8	0.293	0.667	1.31	0.3	0.667	1.61
9	0.150	0.354	0.88	0.154	0.354	0.862
10	0.01	0.01	0.01	0.01	0.01	0.01
11	0.01	0.01	0.01	0.01	0.01	0.01
12	0.175	0.339	0.615	0.177	0.339	0.627
Overall operational time (S.)	11.84	11.44	7.66	11.86	11.14	7.68

3.5. Results of the Proposed Coordination Schemes Based on Different Optimisation Algorithms

Two optimisation methods (PSO and VPS), as common and new powerful optimisation algorithms, respectively, were utilised to determine the optimal coordination setting for all OCRs, and their results were compared to those of the SIC, CVC, and HOC approaches in each of the two power grid scenarios (with and without PV). It is clear from Table 5 that the suggested HOC approach is the best option for reducing the overall operating time of OCRs for both optimisation algorithms (PSO and VPS). In addition, for the SIC, CVC, and HOC approaches, the coordination performance is slightly enhanced by the use of the VPS optimisation algorithm compared to the PSO algorithm. For the power grid connected to PVs, the VPS algorithm achieved an overall tripping time of 7.68, 11.14, and 11.86 s for HOC, CVC, and SIC, respectively, compared to 7.73, 11.25, and 12 s for the PSO algorithm. However, the main improvement in the OCRs' coordination and time-tripping performance was shown through the use of the novel protection scheme in this work (HOC) compared to the SIC and CVC protection schemes.

Table 5. The overall operating time in seconds (S.) of OCRs for the SIC, CVC, and HOC approaches using PSO and VPS optimisation algorithms for the CIGRE network with and without PVs.

Coordination Scheme	**Without PVs**		**With PVs**	
	Optimisation Algorithms			
	PSO	**VPS**	**PSO**	**VPS**
SIC	11.9	11.84	12	11.86
CVC	11.6	11.44	11.25	11.14
HOC	7.7	7.66	7.73	7.68

It is intriguing to examine the convergence rate of the proposed optimisation technique (VPS) under different protection schemes. Figures 9 and 10 depict the convergence curves for the VPS technique under the different protection schemes (SIC, CVC, and HOC) and both power network scenarios (with and without PVs). First, Figure 9 demonstrates and compares the performance of VPS for the SIC, CVC, and HOC schemes for power networks without PV scenarios in terms of convergence. In general, the HOC algorithm has a faster and smoother convergence curve, achieving optimal results compared to SIC and CVC. This shows that the HOC has reduced computation costs while increasing CPU utilisation efficiency. Second, the convergence rate results for a PV power network with PVs are presented in Figure 10. The convergence curve of the HOC is smoother, especially when the number of iterations exceeds 400 while the curves of CVC and SIC were stochastic and volatile over all iterations.

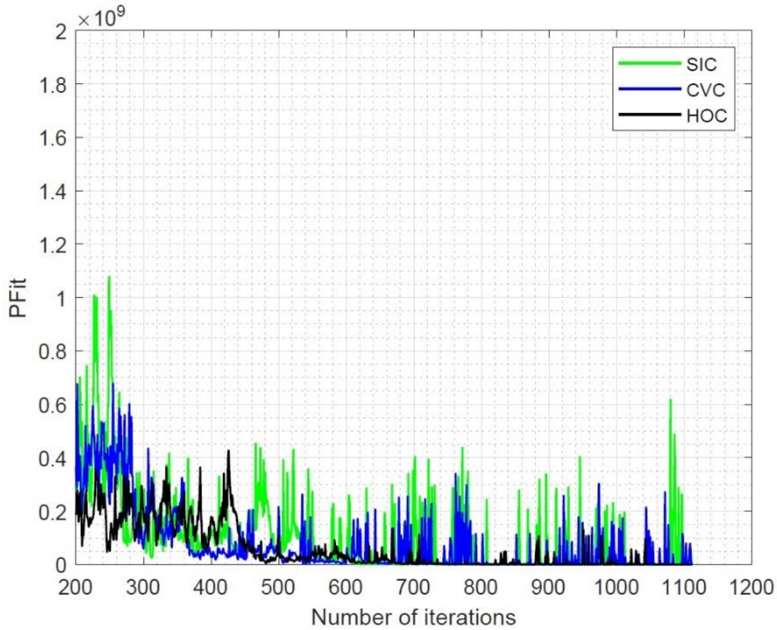

Figure 9. The convergence rate of the VPS technique for power networks without PVs for SIC, CVC, and HOC protection schemes.

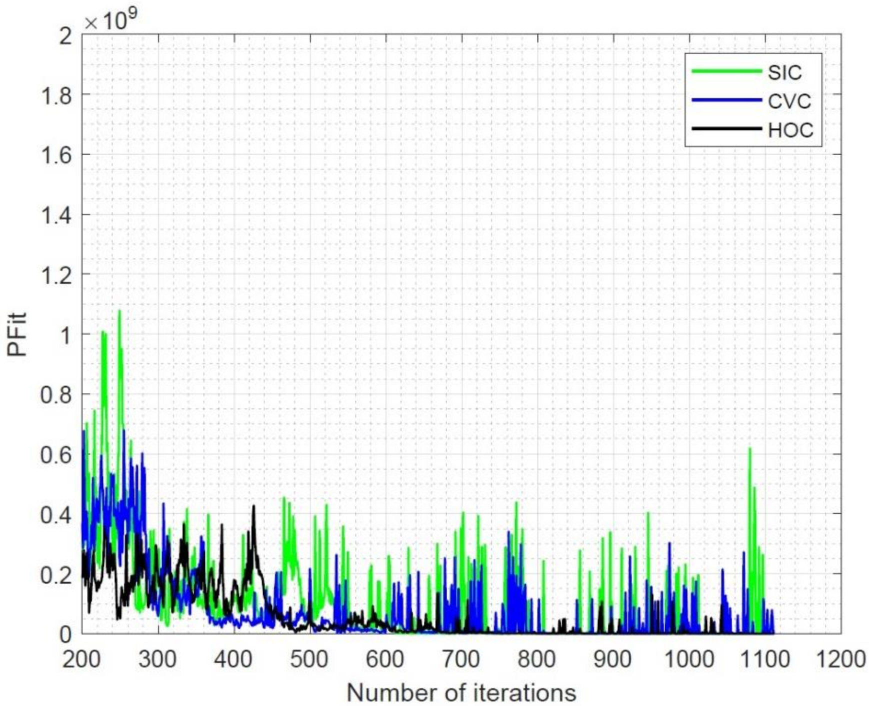

Figure 10. The convergence rate of the VPS technique for power networks with PVs for SIC, CVC, and HOC protection schemes.

3.6. Evaluation Using Industrial Software (ETAP)

ETAP is a typical simulation tool and industrial software that is widely used to show the model of power networks with various types of relays. ETAP is a user-friendly interface for analysing the effectiveness, performance, and viability of protection and power operating systems. In this study, ETAP was used to investigate the performance of OCR settings under different protection schemes (SIC, CVC, and HOC) for the given coordination problem, without introducing misoperation. In this section, a simulation model example was developed to demonstrate optimal OCR coordination utilising ETAP for the power network with PVs using the VPS algorithm, as depicted in Figures 11 and 12. The purpose of these figures is to illustrate the Time Current Curve (TCC) and the OCR coordination between primary and backup OCRs. Figure 11 presents the OCRS coordination between relays 3 and 4 at F2. The proposed HOC scheme outperformed SIC and CVC for the primary relay (4) and the backup relay (3). The primary relay (4) will operate in 0.109, 0.259, and 0.318 s for HOC, CVC, and SIC, respectively. The OCRs coordination at F6 (1.481 Ka at 20 kV) is presented and compared in Figure 12. The proposed HOC scheme recorded the minimum tripping time for primary and backup relays compared to the SIC and CVC schemes. The backup relay at F6 will operate in 0.597, 0.828, and 0.931 s for HOC, CVC, and SIC, respectively.

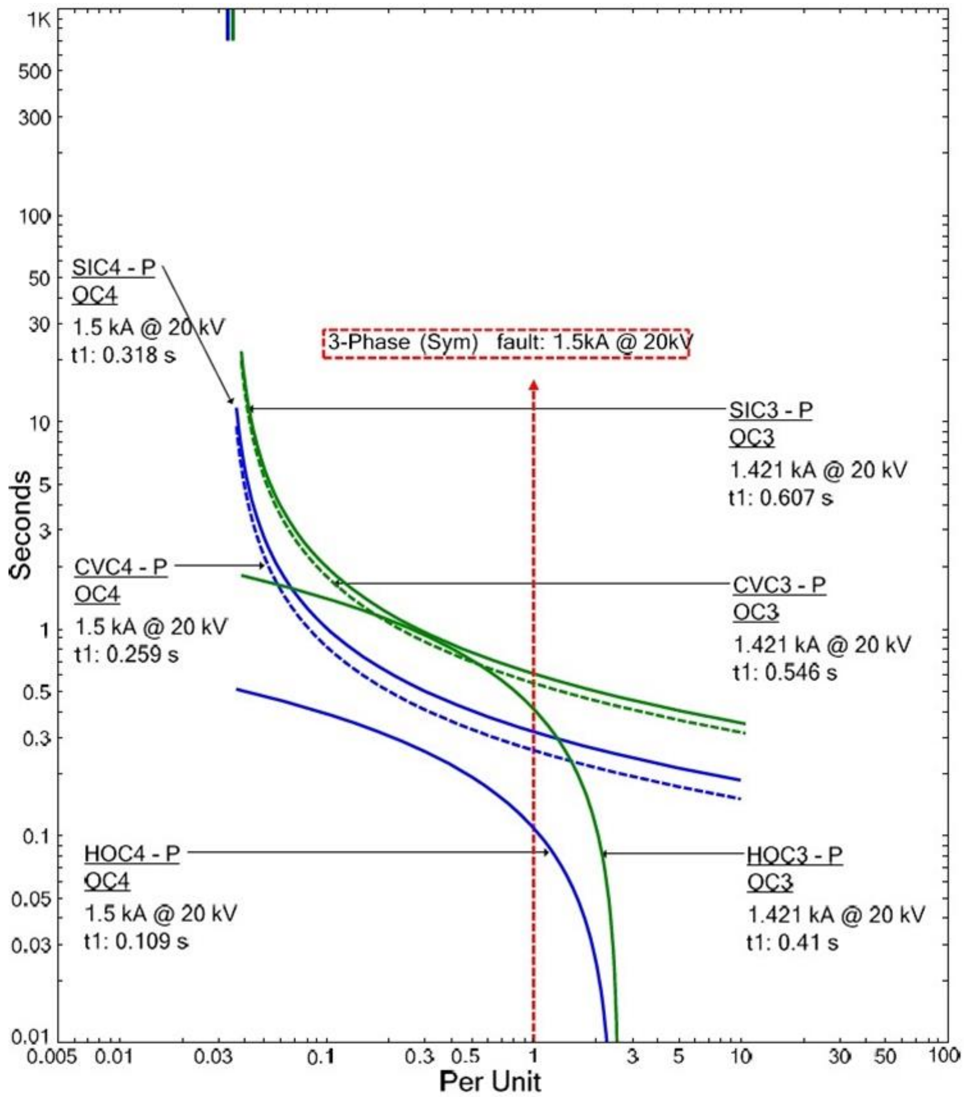

Figure 11. TCC graphs of OCRs for power network with PVs at F2.

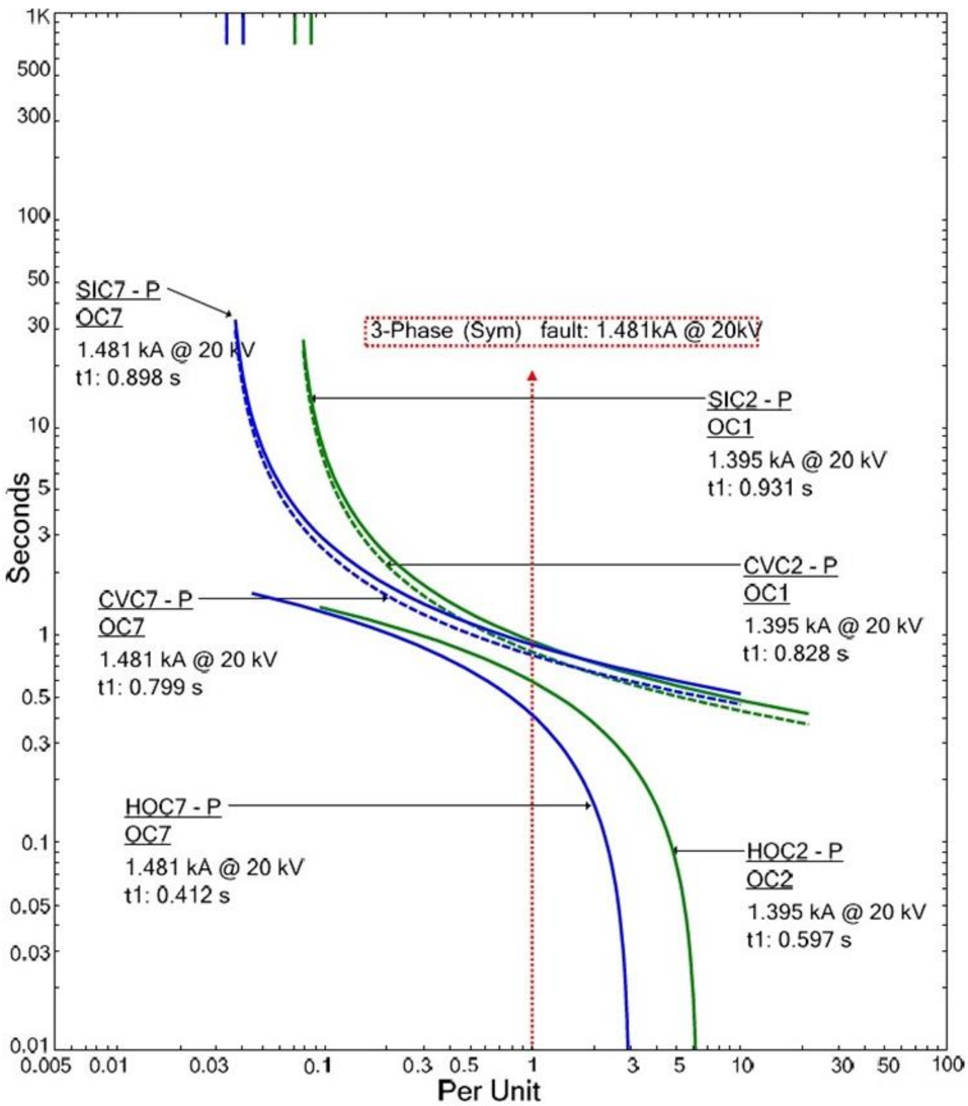

Figure 12. TCC graphs of OCRs for power network with PVs at F6.

4. Conclusions

The goal of this work was to implement a rapid response hybrid tripping scheme for the OCR protection system in modern power network architecture (with and without PVs). The suggested HOC scheme controls and minimises the total operational time for all OCRs by utilizing a new current–voltage characteristic. The optimal OCRs coordination problem under grid constraints was established using the HOC method. The suggested HOC was formulated and solved to provide optimal OCR settings under various fault conditions and different network topologies. The VPS and PSO algorithms were employed to fine-tune and resolve the optimal configuration of all OCRs. The consequences of the suggested HOC approach were not only the fulfilment of the coordination assignment but also a significant reduction in the overall operating time compared to the common SIC and CVC. For example, the overall operational times for the power grid connected to PVs were 11.86, 11.14, and 7.68 s for SIC, CVC, and HOC approaches, respectively. In addition, the VPS and PSO optimisation methods were evaluated to identify a solution with a rapid trip time. The high and complex protection challenges will, in the future, require using machine learning, artificial intelligence, and different optimisation algorithms to minimise the tripping time and improve the protection selectivity performance.

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Nomenclature

CIGRE	Conseil International des Grands Réseaux Electriques	$t_{r,f}$	The operational time of the relay, r, at the fault location, f
PV	Photovoltaic	t_{backup}	Backup OCR
DGs	Distributed generators	$t_{primary}$	Primary OCR
DN	Distribution network	TMS_{min}	Minimum TMS
OCRs	Overcurrent relays	TMS_{max}	Maximum TMS
HOC	The proposed new hybrid tripping OCR scheme	I_f	Fault current
SIC	The common inverse time–current characteristic	I_{pi}	Pickup current
CVC	The time–current–voltage characteristic	A, B	A and B are constants
VPS	Vibrating particles system	V	The phase fault voltage
PSO	Particle swarm optimisation	HOP	Highest optimal position
CTI	Coordination Time Interval	GOP	Good optimal particle
OT	Objective function	BOP	Bad optimal particle
TMS	Time Multiplier Settings	maxNFES	OF evaluation iterations OF evaluation iterations

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