

Grid Protection through Optimal Overcurrent Relay Coordination using Hybrid FA-PSO Technique



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ABSTRACT: The optimal coordination of Overcurrent Relays (OCRs) is vital for guaranteeing the dependable and efficient operation of electricity grids. The increasing complexity of these grids, characterized by diverse fault currents, system configurations, and operating conditions, pose significant challenge to relay coordination (RC). In this study, a novel optimization framework is proposed, Firefly Algorithm (FA) and Particle Swarm Optimization (PSO) techniques were integrated to determine optimal relay settings. The outcomes prove that the proposed hybrid approach ensures optimal RC and thus, minimizes the risk of false tripping. Lower time multiplier settings and relay operating time was achieved in both IEEE three-bus and six-bus systems, and satisfactory Coordination Time Interval (CTI) of backup and primary relays was also achieved. For instance, an average CTI of 0.265s was achieved with FA-PSO, while CTI of 0.308s and 0.290s was attained with FA and PSO techniques for the 3-bus system. This work will aid in the growth of efficient and reliable power grid protection systems, ensuring a stable and secure supply of electricity. The utilized approach is applicable to various grid configurations and can be integrated with existing grid management systems.

KEYWORDS: Overcurrent Relays, Firefly Algorithm, Particle Swarm Optimization, Coordination Time Interval, Optimal Coordination

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I. INTRODUCTION

Power system protection is essential for sustaining the electrical grids' dependability and stability as well as averting critical interruptions. In today's dynamic and intricate electrical grids, traditional protective systems that function on preset fixed settings are insufficient to guarantee system stability and dependability (Islam et al., 2024). The key functions of power system protection are: to reduce damage to electrical systems and the cost incurred in repair and maintenance due to electrical faults, and to protect workers. The timely removal of faulty equipment from service and the early identification and localization of defects depends on these capabilities (Ayhanci et al., 2025; Dickson et al., 2024; Almobasher & Habiballah, 2020). Protective relays provide primary protection in distribution systems. A protective relay (PR) is an apparatus that prompt the circuit breaker (CB) to disrupt the faulty components of the system. Power supply interruptions resulting from faults, overloads, underfrequency, and overvoltage in a power system pose significant threat to the equipment connected to the system (Korde & Bedekar, 2017). In this case, the OCR, a type of PR for sub-transmission and distribution networks, aids in detecting and separating the faulty parts of a network while allowing other parts to continue operating or at least mitigates the operating risk of such parts (Rizk-Allah & El-Fergany, 2021). Relays are therefore made to react quickly to changing system conditions. To improve a

relay's sensitivity and selectivity, optimal RC approaches are employed. OCRs are frequently utilized for power system protection because of their affordability, ease of use, and simplicity. Despite OCRs' simple architecture, the coordination of these relays becomes more difficult as the grid gets bigger and more sophisticated, resulting in time-consuming procedures and higher processing demands (Sadeghi et al., 2024). Relays are usually interconnected; this implies that the operation of a single relay may affect the performance of other network components. In this regard, it is necessary to control the operation of relays, to make them useful for system protection without interfering unduly with other components of the system.

Protection coordination is essential for ensuring uninterrupted supply of power. To ensure protection, the OCR setting must be determined by analysing the short circuit and load flow. To separate the faulty sections of a given network, coordination schemes must guarantee the selectivity, speed, flexibility, and dependability of relay operation. Once the fault conditions are identified by OCRs, the CB will trip and thus, will isolate the affected area from the surrounding areas. OCRs employ both primary and backup protection devices. The backup protection devices will react and trip the CB if the primary protection devices are unable to resolve the issue. Primary relays are used for primary protection. The main task of primary relays is to isolate and de-energize the faulty section of a network to localize the fault on the system and prevent it

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from causing severe damage. However, if the primary relays setup fails for any reason, the backup relays will respond, causing the necessary CBs to trip, and thus, isolate the faulty section after a predetermined user-defined CTI from the moment the fault was first detected. This will then stop any further damage (Agwa & El-Fergany, 2023; Alasali et al., 2023; Kudkelwar & Sarkar, 2019).

Appropriate protection coordination can reduce the consequences of a fault, including the enlargement of fault zones, unnecessary or unwarranted power outages, and equipment casualty. According to the International Electrotechnical Commission (IEC), OCRs attributes use protection coordination, including extremely, very, and normal inverse. OCR typically starts to function when it detects that the load current is higher than a definite value (Kudkelwar & Sarkar, 2019). Plug Setting Multiplier (PSM) and Time Multiplier Setting/Timing Setting Multiplier (TMS/TSM) are critical factors in achieving the best coordination protection. When coordinating protection, plug setting (PS) is found by calculating the maximum load and minimum fault currents (Hussain et al., 2013).

Relay coordination was a labour-and time-intensive procedure in the past as it was carried out manually. However, the use of the simple, outdated conventional procedures proved to be a difficult task due to the expansion of the power network, which involved various load points and sources with the constantly increasing network sophistication. The complexities in deriving the best solution for the coordination problem made it impossible for power system operators not to consider the suboptimal coordination that was satisfying the protection system criteria (Khond & Dhokane, 2019). Diverse strategies have been employed to solve directional OCR (DOCR) coordination problem. Before the discovery of optimization methods, large calculations had to be performed manually, increasing the length of tasks and opportunities for errors. And this was done before computers. Researchers have presented a variety of evolutionary and heuristic algorithms including PSO, Ant Colony Optimization (ACO), Genetic Algorithm (GA), Teaching-Learning-Based Optimization (TLBO), and Differential Evolution (DE), all geared towards addressing the coordination problem of relays in the past. Chen et al. (2013) utilized GA for OCR coordination. They considered the curves of other components of the system like transformers alongside the diverse relay curves. On the other hand, GA was utilized by Choudhary et al. (2015) for determining the operating time and optimal Time Dial Setting (TDS) of OCRs in a distribution network considering its diverse operation modes. For Elsadd et al. (2023) study, their focus was on the utilization of GA along with Homer pro software for communication-less OCR coordination in a power distribution network considering the size, location and size of distributed generations (DGs) within the network. These considerations are vital for effective coordination. With the aid of Cuckoo Search Algorithm (CSA), Rahmania et al. (2019) achieved optimal coordination of OCRs tied to electronic induction networks. The GA method was further enhanced by studies on continuous GA and hybrid GA, which significantly decreased the operation time of relays (Abdullah & Alkhayyat, 2025; Kudkelwar & Sarkar, 2019). More enhancement of other aforementioned methods has been

done as well. Modified adaptive TLBO, modified PSO, and modified adaptive DE are some examples (Fogha et al., 2024). In Bayazidi et al. (2024) study, High Exploration PSO (HEPSO) algorithm was proposed and executed with the aid of bee colony and GA to address miscoordination of relays. Also implemented, was the Turbulent Flow of Water-based Optimization (TFWO). Both TFWO and HEPSO were implemented with consideration of the discrete nature of variables.

Considering relay information (CB tripping time, overshoot time, error), network operators computed fault current and established the allowable time margin for coordination of relays. Utilizing a temporary TMS which can be changed as needed to maintain the discrimination time and a log graph sheet, the current-time feature was plotted using this data (Korashy et al., 2019). Several works have been done on OCR coordination with remarkable success. In the 1960s, computers were utilized to perform sophisticated trial-and-error techniques in order to estimate optimal relay-sequence settings in primitive conventional networks. While these methods successfully solved coordination problems, its utilization was challenging in larger, more complex networks (Ramli et al., 2022). In the late 1980s, Schneider adopted the curve-fitting method using topological analysis and graphical techniques for relay setting. Although this approach was convenient, it lacked precision for currents less than 13/10 times the pickup current. Overall, breakpoint and functional dependence methods based on graph theoretical approaches were also developed to aid in the investigation of relay arrangements. However, these methods also proved inadequate for sophisticated networks with significant levels of DG penetration. Bedekar et al. (2009) introduced a computer-based technique where a graphical user interface was utilized to solve the coordination problem of DOCRs in multi-DG power networks. However, it failed to progress in the face of miscoordination. Traditional OCRs use time-current characteristic (TCC) curves to operate. A comprehensive study on TCC curves for inverse and very inverse relays was conducted by Chukwuoko et al. (2024) and the focus of the study was on computing the optimal settings for relay operation and protection. For Yazdaninejadi et al. (2018), they introduced an auxiliary parameter that aided in attaining optimum TCCs. Thus, a quick and better protection was achieved. Al-Bhadely & Inan (2024) established a new on-line adaptive protection strategy for relay coordination in distribution networks. DOCRs acceleration, selectivity and sensitivity was enhanced with their proposed method. Survey on the utilization of diverse optimization methods for enhanced coordination of DOCRs in interlinked electricity networks was done by Ramli et al. (2021). Hussain et al. (2013), in their study, introduced innovative strategies for configuring DOCR by employing meticulously designed objective functions and protective devices. Optimization techniques are utilized to ensure the creation of accurate and dependable protection schemes for DNs (Distribution Networks) with DG. Various researchers have examined RC as a Non-Linear Programming (NLP) problem that can be handled utilizing diverse optimization strategies. Nevertheless, these approaches are difficult and time-consuming. Furthermore, General Algebraic

Modelling System (GAMS) have been utilized to represent relay coordination as a mixed integer NLP (MINLP) problem (Bedekar & Bhide, 2010; Noghabi et al., 2009). Tiwari et al. (2022) followed the path but in their case, the optimum settings of the relays were ascertained using Grey Wolf Optimization (GWO) and GA. To simplify the coordination of OCRs, Linear Programming (LP) methods like the 2Ø simplex, dual simplex, and simplex methods have irregularly been utilized (Tripathi et al., 2022; Singh et al., 2011; Bedekar et al., 2010; Rashtchi et al., 2010) or utilized considering the dynamics of the system under investigation (Alcala-Gonzalez et al., 2022). Nevertheless, these techniques can become stuck in local optima because they rely on initial estimates (Moravej et al., 2012).

Godwal et al. (2023) proposed a novel objective function (OF). The work started by examining the conventional OF already existing in literature and subsequently established the drawbacks associated with the traditional OF. They demonstrated how their proposed OF will aid in addressing possible occasions of relay miscoordination as well as ensure optimum operation time of relays. While for El-Fergany (2016), aside from proposing a new OF, Flower Pollination Algorithm (FPA) was used to provide an optimal solution to OCRs selection problem. For Mohamed & Idris (2022), they examined OCR coordination in ring, radial and interlinked distribution systems. Radial Basis Function Neural Network (RBFNN) was utilized by Uma et al. (2023) while clonal selection algorithm based-Artificial Immune System (AIS) was utilized by Hatata et al. (2020), both in a distribution system with DG, for the effective coordination of the relays in the network. The notable characteristics of the RBFNN in Uma et al. (2023) study, is its capability of dynamically adjusting the PSM and TSM settings of the OCR. Furthermore, on DG-linked DNs, Sookrod & Wirasanti (2018) suggested a RC tool as a way of overcoming OCR coordination problem. Coordination of OCRs can be an issue depending on the nature of the network. This led Javadi et al. (2018) to assess OCRs coordination problem in energy storage as well as wind power production systems.

Korashy et al. (2021) in their study, considered both the non-traditional and traditional features of OCRs in order to determine the best method to employ for effective coordination. In light of this, they proposed Water Cycle Algorithm (WCA) and modified WCA as well as Moth Flame Optimization (MFO) and enhanced MFO, as a solution to DOCR coordination problem. Meanwhile, Round off Mixed Integer PSO (ROMI-PSO) was executed by Plongkrathok et al. (2023). The authors were able to demonstrate that with the use of the proposed approach, the coordination and operating time of relays can be significantly enhanced.

Manual and heuristic strategies still have major flaws including optimization time dampening and ineffectiveness with respect to attaining the best results. The more integrated and complex the power grid become, the more apparent the flaws of traditional methods are to give way to advanced optimization strategies (Tomar et al., 2023). Thus, in this present study, the main focus is on optimal coordination strategy for OCRs in an interlinked power system (IEEE 3-bus

and 6-bus systems were utilized as case studies) using FA-PSO technique. To achieve this, first the model of the IEEE 3-bus and 6-bus systems was carried out. Thereafter, the FA-PSO technique was implemented on both models alongside FA and PSO individual techniques. Furthermore, the three methods were compared using the metrics: relay operating time, CTI and TMS. The FA-PSO approach represents a notable development in OCR coordination, providing a high-performance, flexible, and efficient strategy that enhances fault protection in today's interconnected power systems. The proposed Firefly-PSO method provides a valuable contribution towards overcoming the limitations associated with the coordination of OCRs in interlinked power systems. Thus, the approach can improve coordination in large-scale grids prone to dynamic occurrences like load variations, topological changes, and the integration of distributed energy resources, by managing vast quantities of relays and complex fault situations. Furthermore, the hybridization of the FA-PSO technique is unique, in that, it is a suitable optimization tool since the global searching capability of FA and accelerated convergence property of PSO was explored to find the optimum setting of relays in the interconnected system.

The structure of the remaining part of this paper is as follows: section II - theoretical framework, section III - methodology, section IV - results and discussion and section V - conclusion.

II. THEORETICAL ANALYSIS

A. Coordination Problem Formulation

The coordination of directional OCRs is an optimization issue which is complicated by several non-linear and linear inequality constraints. Before the coordination problem can be defined, the objective function (OF) first needs to be defined. These also include the relay configuration and relay selectivity constraints (Foqha et al., 2023). These many constraints make the coordination of OCRs in interlinked networks a complex problem. Formation and coordination of OC relays consist of three essential components: high speed operation of relays, selectivity (where fault in a particular protection zone causes the associated relays to operate), and reliability (where a secondary relay operates when the main relay fails to trip).

B. Objective Function

In addressing OCR coordination problem, the aim is to reduce the relays' operation time, the primary relays' overall operating time, the relays' coordination time, and any miscoordination problems that may occur on failure of the primary protection zone, and the objection function (Abdullah & Alkhayyat, 2025; Kida et al., 2020) in this regard is given as Equation (1).

$$OF = \sum_{i=1}^N T_{op,i} \quad (1)$$

The operating time of the relay, T_{Op} can be calculated using Equation (2).

$$T_{Op,i} = TMS_i x \frac{\alpha}{\left(\frac{I_f}{PS_i x CTR}\right)^\beta - 1} \quad (2)$$

Where I_f is the fault current; CTR (Transformer Current Ratio); β and α are relay constants, TMS is Time Multiplier Setting.

C. Relay Characteristic Constraints

There are limitations on cooperation between the main and secondary relays. If the protection system is to be satisfied, the primary relay's operational duration should be less than that of the backup relay (Abdullah & Alkhayyat, 2025; Foqha et al., 2023). In order to eliminate the affected portion of the network, it means that the main protection must resolve the issue as quickly as possible.

D. Coordination Time Interval

The Coordination Time Interval (CTI) in the context of overcurrent relay coordination is defined as the minimum required time difference between the operation time of the main relay (t_p) and the backup relay (t_b), for a fault happening at position k (Abdullah & Alkhayyat, 2025; Abeid & Hu, 2020). Notably, Equation (3) is a proper way to state the coordination constraint.

$$t_{b,k} - t_{p,k} \geq CTI \quad (3)$$

Where $t_{b,k}$ and $t_{p,k}$ are the operation times of the backup and main relays for a fault at location k .

E. Time Multiplier Settings

Finding the Time Multiplier Settings (TMSs) for upper and lower boundaries is essential to obtain an ideal setup outcome. The requirements supplied by the protection relay producers can be used to establish the TMSs restrictions. Equation (4) describes the TMSs limitations (Abdullah & Alkhayyat, 2025; Foqha et al., 2023; Abeid & Hu, 2020).

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \quad (4)$$

Where $TMS_{i,min}$ and $TMS_{i,max}$ denote the TMSs lower and upper bounds, respectively, for the i -th relay.

F. Plug Settings

The bounds of the Plug Setting (PS) for every relay may be determined using Equation (5) and it determines the minimum current required to initiate the operation of the relay. Also, the PS is determined by the system's full load current and short-circuit level (Abdullah & Alkhayyat, 2025; Foqha et al., 2023; Abeid & Hu, 2020).

$$PS_{i,min} \leq PS_i \leq PS_{i,max} \quad (5)$$

where $PS_{i,min}$ and $PS_{i,max}$ represent the minimum and maximum PS boundaries of the i -th relay accordingly.

G. Operating time

The relay operating time is expected to be within specified limits. This limit is given (Abdullah & Alkhayyat, 2025) as Equation (6).

$$T_{Op,min} \leq T_{Op,i} \leq T_{Op,max} \quad (6)$$

Where $T_{Op,max}$ is the thermal limit of component that is protected and $T_{Op,min}$ is usually specified by the relay producer.

H. Genetic Algorithm

A nature-inspired optimization technique known as FA is used to tackle challenging, highly nonlinear restricted situations. Xin-She Yang suggested the FA in late 2007 and early 2008, drawing inspiration from the activity of fireflies at Cambridge University. To create this algorithm, three idealized rules were used. Rule one states that fireflies are universally attracted to each other, irrespective of sex. Rule two states that each firefly's brightness and beauty have an inverse relationship. This further imply that fireflies are drawn to one another more readily when they are brighter. That being said, fireflies lose some of their brilliance and appeal as they become farther apart. According to the third rule, each firefly's luminance is determined by the OF's value. Larger light-intensity fireflies have lower objective functions in minimization problems (Yang & Xingshi, 2013). The generalized FA procedure involve the under listed steps:

Step 1: Initialization

- i. Define the OF (say, $f(x)$) to be minimized or maximized
- ii. Initialize parameters such as max-iteration (the stop criterion); N (population size – number of fireflies); γ (absorption coefficient of light); α (randomization parameter); β_0 (attractiveness)

iii. Generate initial population

Step 2: Compute brightness and light intensity

- i. The light intensity, I of a firefly at a specific location x is directly proportional to the OF.

$$I_i \propto 1/f(x_i) \text{ for minimization problems}$$

$$I_i \propto f(x_i) \text{ for maximization problems}$$

Step 3: Commence iterative update on the main loop

Repeat the underlisted steps until the stopping criterion is achieved:

- a. Loop through all fireflies – for each firefly i from 1 to N . Compare with other fireflies for every other firefly j from 1 to N . Then check for brightness – if firefly j is brighter than i ($I_j > I_i$), i is attracted to j and thus moves to its position. Compute distance (r_{ij}) and β using Equations (7)-(8).

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^d (x_{i,k} - x_{j,k})^2} \quad (7)$$

$$\beta(r_{ij}) = \beta_0 e^{-r r_{ij}^2} \quad (8)$$

Thereafter, update position of i as it moves towards j using Equation (9).

$$x_i^{t+1} = x_i^t + \beta(r_{ij})(x_j^t - x_i^t) + \alpha(rand - 0.5) \quad (9)$$

where $\beta(r_{ij})(x_j^t - x_i^t)$ is the attraction component; $\alpha(rand - 0.5)$ is the randomization component with $rand$ = random number between 0 and 1. If i is the brightest firefly within its location. It moves arbitrarily utilizing only the randomization term as given in Equation (10).

$$x_i^{t+1} = x_i^t + \alpha(rand - 0.5) \quad (10)$$

b. Compute the new I_i for all updated firefly locations x_i^{t+1}

c. Update global best – by storing the present best-found location (solution) among all fireflies.

Step 4. Stop - this indicates that the optimal solution has been found

I. Particle Swarm Optimization

A possible solution to an optimization problem is represented by each entity known as a particle. The best information gathered during the solution area exploration is stored in the memory of a particle in PSO, just like in any living entity. The PSO as developed by (Kennedy & Eberhart, 1995) has the following (Shi & Eberhart, 1998) steps as indicated in Table 1.

Table 1: PSO algorithm

Step	Description
1	Initialization
i.	Define the OF ($f(x)$) to be maximized or minimized
ii.	Initialize hyper-parameters such as N (number of particles in the swarm); c_1 (cognitive coefficient); c_2 (social coefficient); w (inertia weight); max-iteration
iii.	Initialize particle positions (x_i)
iv.	Initialize particle velocities (v_i)
v.	Initialize personal best ($pbest_i$) and global best ($gbest$)
2	Commence iterative update on the main loop
	Repeat the underlisted steps until the stopping criterion is achieved:
a.	Evaluate fitness by computing $f(x_i)$ for the current position of every particle x_i in the swarm
b.	Update $pbest_i$
c.	Update $gbest$

-
- d. Update v_i
Use Equation (11) to compute the new v_i for each particle i .
 - e. Update x_i using Equation (12)
 - 3 Stop – this indicates that the optimal solution has been found
-

$$v_i(t+1) = wv_i(t) + c_1r_1(pbest_i - x_i(t)) + c_2r_2(gbest - x_i(t)) \quad (11)$$

Where r_1 and r_2 are random numbers and range from 0-1; $wv_i(t)$ is inertia term; $c_1r_1(pbest_i - x_i(t))$ is cognition term; $c_2r_2(gbest - x_i(t))$ is the social term.

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (12)$$

J. Hybrid Firefly-Particle Swarm Optimization Technique

The Hybrid FA-PSO technique merges the ability of the FA to explore the search space with the capability of PSO to exploit the solution. The FA is able to help the search process get out of local optima by utilizing the functions of attractiveness and brightness, while PSO makes the convergence faster and more accurate by means of velocity and position updates. The hybrid FA-PSO technique involve the following steps:

Step 1: Initialization - Create initial population (relay setups) randomly within specified bounds. Also, initialize other parameters (α , β_0 , c_1 , w , c_2).

Step 2: Fitness Evaluation - Assess the objective function (total relay operating time).

Step 3: FA Phase - The brighter fireflies to move are selected using β_0 and γ . Random movement is then added to retain diversity. Thus, Equation (9) is applied.

Step 4: PSO Phase - Apply Equation (11) and update position using Equation (12).

Step 5: The $gbest$ solution from PSO is combined with FA best solution.

Step 6: Hybridization Strategy - On each iteration, the algorithm switches from FA to PSO or vice versa. The convergence is controlled by the inertia weight, w and β_0 parameters.

Step 7: Stopping Criteria - The iterations stop once the maximum number of iterations is attained.

The flowchart of the FA-PSO technique utilized in this study is depicted in Figure 1.

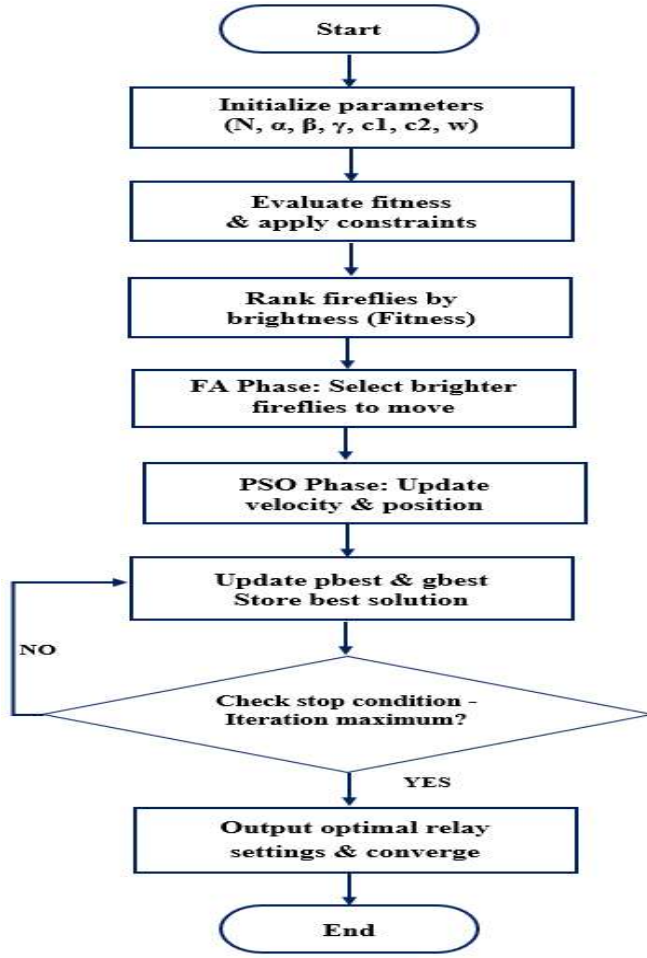


Figure 1: Flowchart of the FA-PSO technique

III. METHODOLOGY

The FA-PSO technique parameters is depicted in Table 2 while that of the OCR, in Table 3. The FA-PSO parameters selected guarantee a proper balance between computational efficiency and the convergence accuracy. The hybridization of the FA with PSO brings about an improvement in the robustness characteristics, that is, PSO can speed up the convergence in the vicinity of the global optimum whereas FA makes certain that the algorithm can escape local minima by adaptive exploration. A population size of $N = 50$ and a maximum of 100 iterations was utilized. The inertia weight, w was changed gradually from 0.9 to 0.4 to allow more local refinement in the later iterations, whereas the adaptive randomization parameter, α was utilized to support global search at the beginning and local search near convergence. The hybrid switch ratio of every five iterations ensures that the global and local search processes are effectively coordinated, and the absorption coefficient $\gamma=1.0$ was used to maintain moderate attractiveness decay so as not to cause clustering. The FA-PSO algorithm stops when the iteration limit is reached. The change in global best fitness rate is less than 10^{-5}

or the population converges within 10% of the best fitness value. As a result, the FA-PSO technique returns the optimal TMS and PS currents (I_{PS}) that lead to minimum total relay operating time while meeting coordination constraints.

Table 2: FA-PSO Technique Parameters

Parameter	Symbol/Unit	Value/Range
Population size	N	50
Maximum iterations	Max-Iter	100
Light absorption coefficient	γ	1.0
Initial attractiveness	β	1.0
Randomization parameter	α	0.2 (adaptive)
Inertia weight (PSO)	ω	0.9 \rightarrow 0.4 (linearly decreasing)
Cognitive acceleration	c_1	2.0
Social acceleration	c_2	2.0
Convergence tolerance		1×10^{-5}
Hybrid switch ratio		Every 5 iterations

Table 3: OCR Parameters

Parameter	Symbol/Unit	Value/Range
Time Multiplier Setting	TMS_i	0.05 – 1.2
Plug Setting	I_{PS}	$0.5 - 1.5 \times \text{rated current}$
Relay curve type		Standard Inverse (SI)
Relay constants	β, α	0.14, 0.02
Minimum operating time	$T_{OP,min}$	0.1s
Backup relay delay	$(t_b - t_p)$	$\geq 0.3s$

A. IEEE 3-Bus System

IEEE 3-bus and 6-bus system were utilized as case studies in this work. The former is shown in Figure 2. It comprises of three interconnected buses and generators, six DOCRs and three branches, making it easier to analyze relay settings and fault currents. By reducing operating time and increasing selectivity, it provides a useful environment for testing hybrid optimization techniques such as FA-PSO, to improve relay coordination. Conventional IEEE 3-bus system was utilized to

evaluate how well the suggested method reduced the operating time of DOCRs.

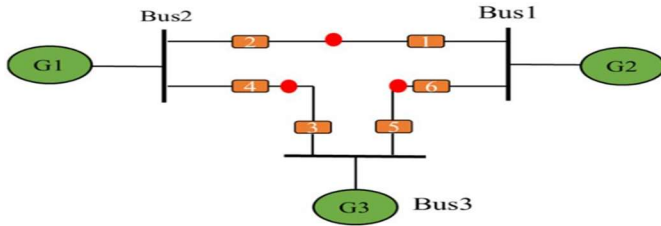


Figure 2: One-line diagram of IEEE 3 bus network (Wadood & Park, 2024)

B. IEEE 6-Bus System

The IEEE 6-Bus system is shown in Figure 3, and it offers a realistic environment for examining interactions between protective devices since it has a more intricate network with numerous generators and loads. Researchers can assess relay settings under a range of fault circumstances and scenarios. The network features fourteen CBs, four power generators, six buses and branches. The study's main goal is to enhance the settings of the fourteen relays tied to the CBs in order to identify the optimal TMS and PS.

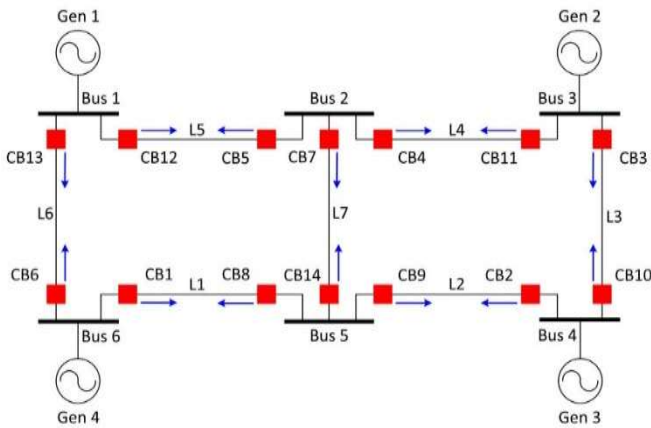


Figure 3: Single-line schematic of an IEEE 6-bus network (Al-Roomi & El-Hawary, 2019)

C. Simulation Process

The simulation process was done in MATLAB R2024b, using the optimization toolbox as well as custom-coded scripts for modelling the power system network, fault analysis, and relay settings optimization. The main steps of the simulation are outlined below:

- Input network data (bus, line, and relay parameters).
- Conduct load flow and short-circuit analysis to obtain the fault currents.
- Set up optimization parameters and create the initial population.
- Calculate relay operating times using IEC curve equation.

- Use hybrid FA-PSO algorithm to find minimum total operating time while satisfying CTI constraints.
- Save the optimized TSMs, operating times, and CTIs for reference.
- Assess the effectiveness of FA, PSO, and hybrid FA-PSO techniques.

D. Simulation Model

MATLAB/Simulink environment was utilized to model the IEEE 3-Bus and 6-bus power system. The model includes line impedances, load data, and power generation. The hybrid FA-PSO for relay coordination was implemented using the optimization toolbox embedded in the software in addition to custom-coded scripts. IDMT (Inverse Definite Minimum Time) relay block as depicted in Figure 4, was utilized alongside circuit breakers for initiating trip actions in case of a fault event. This relay block combines an instantaneous relay with an IDMT OCR, which activates when current passes a preset threshold. Furthermore, the simulation model for OCR coordination for the IEEE 3 and 6-bus test power systems is depicted in Figures 5 and 6 respectively.

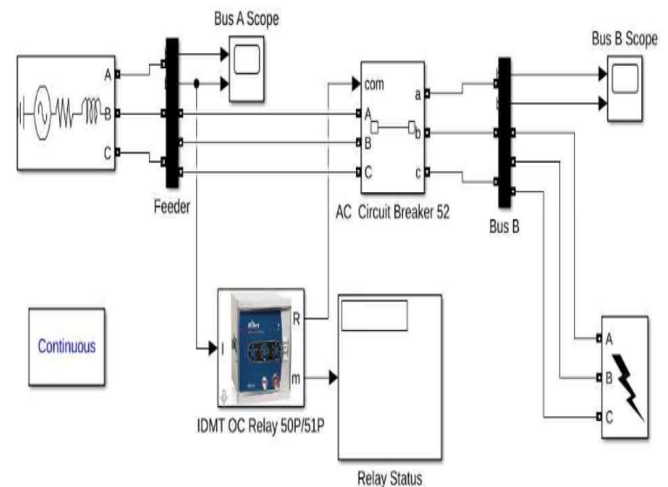


Figure 4: IDMT overcurrent relay block with other components (Tan, 2021)

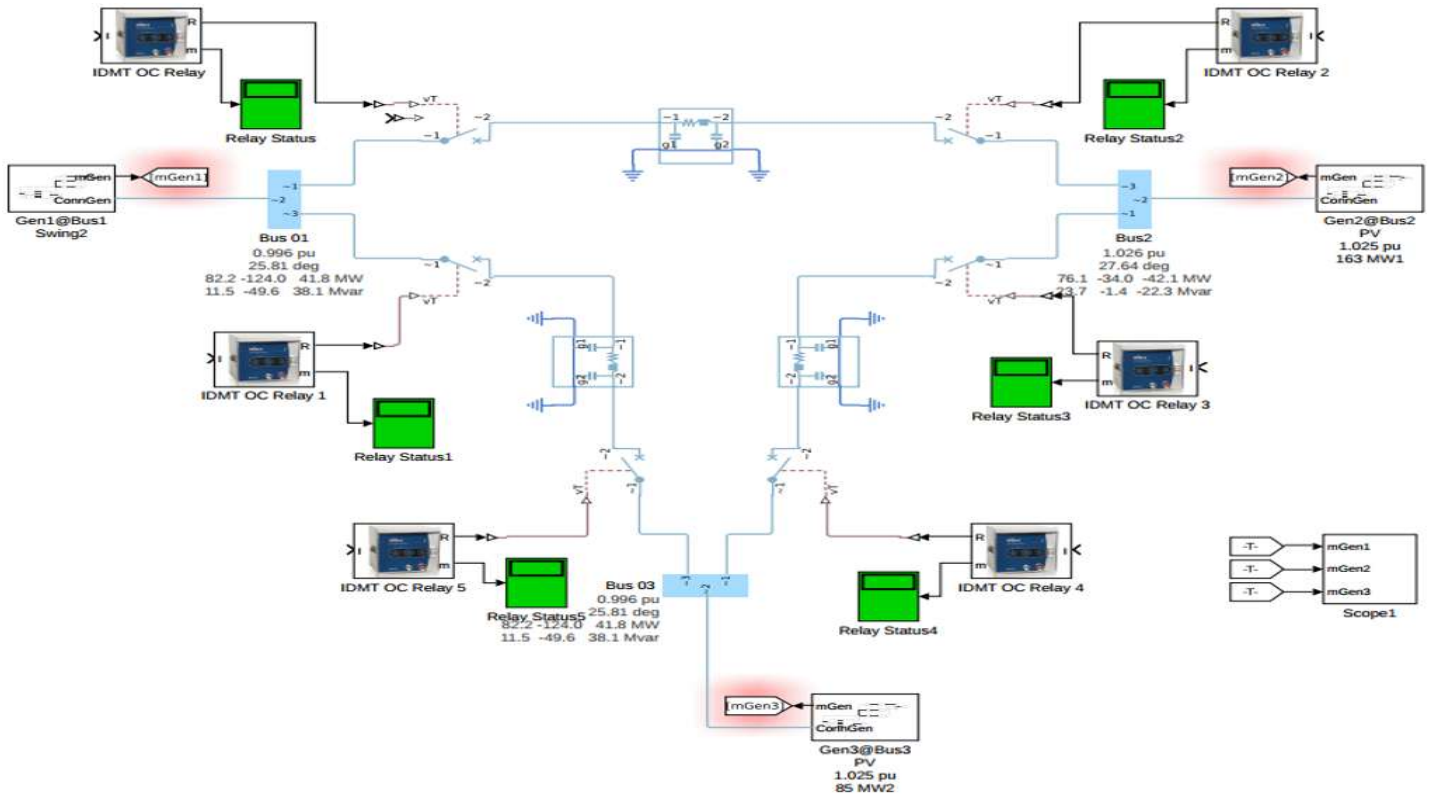


Figure 5: Simulation model for OCR coordination in IEEE 3-bus system

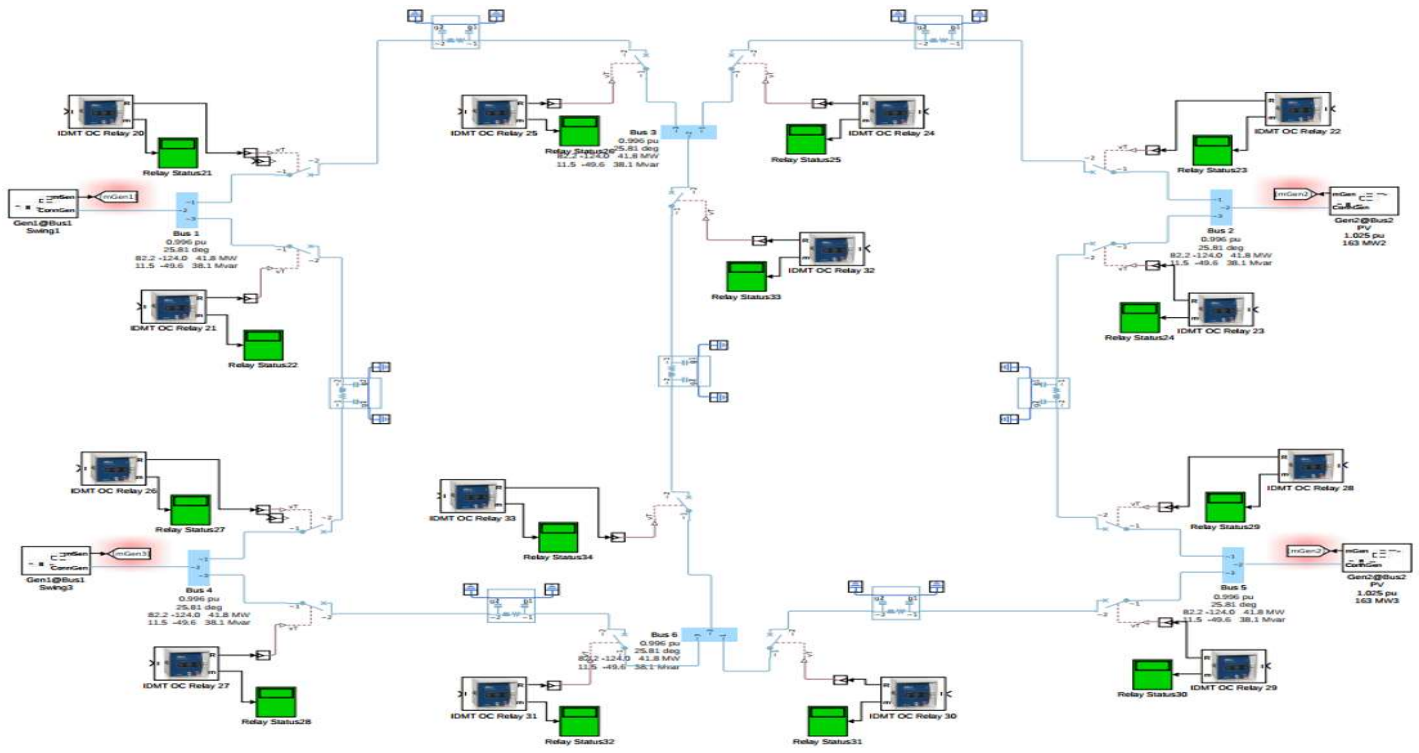


Figure 6: Simulation model for OCR coordination in IEEE 6-bus system

E. Relay Parameter Settings

Relay setup settings for OCR coordination are essential for minimizing fault clearing time, preventing needless trips, and guaranteeing that relays trip in the right order and with the right time delays. CTR of the relays was selected based on the maximum load current of the system and the anticipated fault current. The CTR of the relays in the IEEE 6 and 3-bus test systems are depicted in Table 4.

Table 4: Relay CTR for the 3 and 6-Bus Test Systems

Relay Number	3-Bus System CTR	6-Bus System CTR
1	200/5	1200/5
2	300/5	800/5
3	200/5	800/5
4	300/5	800/5
5	300/5	800/5
6	400/5	1200/5
7		800/5
8		800/5
9		800/5
10		600/5
11		800/5
12		800/5
13		1200/5
14		800/5

The system's short circuit current (SCC) was determined using impedance values from the system model, including generator, transformer, and line impedances. The 3 ϕ SCC for the main and backup relays utilized in the test bus systems are depicted in Tables 5 and 6.

Table 5: 3 ϕ SCC of the Backup and Primary Relays of the 3-Bus System

Primary Relay	SCC (A)	Backup Relay	SCC (A)
1	1978.20	5	178.00
2	1531.70	4	543.00
3	1682.60	1	616.22
4	1813.10	6	464.17
5	1495.62	3	385.20
6	1766.40	2	142.64

Fault analysis is usually utilized to calculate fault currents at different points within a given system for both symmetrical and non-symmetrical faults. Hence, all relays are usually configured with important parameters like TDS and PS that impact its operating time. The PS of the relays for the test bus systems are depicted in Tables 7 and 8. When there is an abnormal condition in a network, the main relays operate first, clearing the fault while the backup relays clears the identified fault after a CTI if the main relays fails. This coordination prevent malfunctions and limits the fault consequence on the network.

Table 6: 3 ϕ SCC of the Backup and Primary Relays of the 6-Bus System

Primary relay	SCC (kA)	Backup relay	SCC (kA)
1	18.1720	13	0.6010
2	4.8030	3	1.3650
3	30.5470	4	0.5528
4	5.1860	12	3.4220
5	2.8380	14	1.7640
6	18.3380	8	3.4220
7	4.4960	11	0.7670
8	2.3510	7	1.4830
9	6.0720	1	4.5890
10	4.0770	9	0.6390
11	30.9390	10	0.9455
12	17.7050	6	0.8610
13	17.8210	5	0.9770
14	5.4570	2	0.8680

Table 7: OCR PS Values (3-Bus System)

Relay number	PS Value
1	1.3
2	1.5
3	1.2
4	1.4
5	1.3
6	1.2

Table 8: OCR PS Values (6-Bus System)

Relay Number	PS Value
1	1.7
2	2.2
3	2.5
4	1.9
5	2.0
6	2.1
7	2.0
8	1.8
9	2.5
10	2.8
11	2.0
12	2.5
13	3.0
14	2.0

IV. RESULTS AND DISCUSSION

The OCR coordination results from the proposed FA-PSO technique is presented in this section. The efficiency of the method is also demonstrated by comparing it with other individual techniques (FA and PSO). Furthermore, the suggested method is assessed using IEEE 3-bus and 6-bus systems.

A. Result on Time Multiplier Setting

The TMS is important for coordination of relays, since the delay before a relay operates is controlled based on it.

Tables 9 and 10 demonstrates the optimal TMS parameters attained using FA and PSO techniques independently, and then, the proposed hybrid method (FA-PSO) on IEEE 3-bus and 6-bus systems respectively. With the hybrid FA-PSO method, minimum TMS values was achieved for all relays on the bus systems. This will, therefore, yield faster operating times and better relay coordination. Furthermore, TMS values with FA alone is high compared to the PSO technique, where a lower outcome was attained across all the relays. The high TMS values obtained with FA will result in slower fault clearance and coordination. Specifically, a total TMS of 0.817 and 2.319 was achieved for the 3-bus and 6-bus systems respectively, using the proposed hybrid technique compared to TMS values attained with FA (1.207 and 3.290) and PSO (1.021 and 2.953) independently. Thus, this indicates that the hybrid FA-PSO approach is better suited for relay coordination and fault clearance.

Table 9: TMS Result (3-Bus System)

Relay Number	FA	PSO	FA-PSO
1	0.123	0.102	0.080
2	0.147	0.125	0.092
3	0.182	0.151	0.124
4	0.257	0.212	0.162
5	0.130	0.116	0.087
6	0.368	0.315	0.272
Total TMS	1.207	1.021	0.817

Table 10: TMS Result (6-Bus System)

Relay Number	FA	PSO	FA-PSO
1	0.213	0.181	0.120
2	0.147	0.125	0.092
3	0.124	0.108	0.090
4	0.332	0.314	0.217
5	0.130	0.116	0.087
6	0.281	0.254	0.201
7	0.413	0.402	0.363
8	0.182	0.151	0.124
9	0.186	0.173	0.129
10	0.265	0.245	0.202
11	0.368	0.315	0.272
12	0.151	0.123	0.104
13	0.257	0.212	0.162
14	0.241	0.234	0.156
Total TMS	3.290	2.953	2.319

B. Result on Relay Operating Time

Relay operating time (ROT) is crucial as it ensures the stability of the power system and reduces the impact of faults. The primary objective in the context of this study is to optimize (that is, reduce) the operating time of the relays. This will ensure that faults are promptly cleared. The ROT result considering the three techniques is depicted in Tables 11 and 12. Again, the FA-PSO technique with a total ROT of 7.515 seconds for the 6-bus system and 2.696 seconds for the 3-bus system, outperformed the other methods. Meanwhile, following closely behind the hybrid approach, is the PSO technique, with a total ROT of 2.929 seconds and 8.3954 seconds respectively for the 3-bus and 6-bus systems.

Table 11: Relay Operating Time (3-Bus System)

Relay Number	FA (Operating Time [s])	PSO (Operating Time [s])	FA-PSO (Operating Time [s])
1	0.343	0.326	0.307
2	0.645	0.61	0.562
3	0.382	0.345	0.312
4	0.686	0.628	0.578
5	0.402	0.358	0.331
6	0.719	0.662	0.606
Total ROT	3.177	2.929	2.696

Table 12: Relay Operating Time (6-Bus System)

Relay Number	FA (Operating Time [s])	PSO (Operating Time [s])	FA-PSO (Operating Time [s])
1	0.413	0.382	0.348
2	0.705	0.654	0.587
3	0.442	0.396	0.357
4	0.726	0.6634	0.602
5	0.452	0.423	0.384
6	0.756	0.715	0.634
7	0.478	0.445	0.415
8	0.782	0.73	0.682
9	0.513	0.479	0.432
10	0.82	0.763	0.692
11	0.557	0.524	0.462
12	0.861	0.821	0.712
13	0.585	0.552	0.483
14	0.885	0.848	0.725
Total ROT	8.975	8.3954	7.515

C. Result on Coordination Time Interval

CTI plays a key function in OCR coordination, defining the minimum time interval between the actuation of relays when fault conditions are present. Satisfactory CTI allows primary relays to operate first before the backup relays when the primary relays fail. Unnecessary tripping of backup relays is prevented with optimum CTI. Thus, this enhances the system reliability and reduces downtime. The CTI for the secondary and main relay pairs is depicted in Tables 13 and 14 for each bus system considering the techniques under investigation.

Table 13: CTI of Relay Pairs (3-Bus System)

Primary Relay	Backup Relay	FA	PSO	FA-PSO
1	2	0.302	0.284	0.255
3	4	0.304	0.283	0.266
5	6	0.317	0.304	0.275
Total operating time (secs)		0.923	0.871	0.796
Average coordination time (secs)		0.308	0.290	0.265

Table 14: CTI of Relay Pairs (6-Bus System)

Primary Relay	Backup Relay	FA	PSO	FA-PSO
1	2	0.292	0.2720	0.239
3	4	0.284	0.2674	0.245
5	6	0.304	0.2920	0.250
7	8	0.304	0.2850	0.267
9	10	0.307	0.2840	0.260
11	12	0.304	0.2970	0.250
13	14	0.300	0.2960	0.242
Total coordination time (secs)		2.095	1.9934	1.753
Average coordination time (secs)		0.299	0.2850	0.250

Results from Tables 13 and 14, indicates that the FA-PSO technique is superior to FA and PSO individual techniques, both from the relay pairs to the total coordination times. From the 6-bus system, the FA-PSO demonstrated its superiority with a total and average coordination times of 1.753 and 0.250 seconds respectively. That of the FA method lagged the PSO method, as the total and average coordination times for the 6-bus system was 2.095 and 0.299 seconds for the former, and 1.9934 and 0.2850 seconds for the later. To support the fact that the hybrid combination (FA-PSO) is better, with the 3-bus system, 0.796 and 0.265 seconds were the total and average coordination times. Again, considering the 3-bus system, the results indicates that the FA method was the least performing,

as the highest total and average coordination times (0.923 and 0.308 seconds) were obtained with the technique.

Overall, results from the considered metrics: ROT, CTI and TMS, indicates that the FA-PSO technique is a good alternative for achieving reduced relay operation time and optimal relay coordination.

V. CONCLUSION

The proposed hybrid method leverages the global search ability of the FA with the fast convergence of PSO to obtain the optimal relay settings such that coordination constraints are satisfied. It reduces relay operation times for optimum fault clearance as this will ensure continuous grid operation. This hybrid approach can indeed be advantageous, enabling it to better handle the complexities associated with interlinked systems, like counter current power flow and high fault levels. The strong function of exploring high-dimensional search spaces makes it applicable for large-scale networks, while its flexibility enables it to be integrated into grids with dynamic topology or lower load conditions. The Firefly-PSO technique converges more quickly and provides high-quality solutions than the individual techniques.

Furthermore, FA-PSO's better scalability and weightiness lead to concrete benefits such as reduced fault duration and higher system reliability. Thanks to these benefits, the proposed approach thus, can serve as a useful aid for contemporary power grids, and as well, can deal with challenges such as renewable power incorporation and aging infrastructure. The use of machine learning techniques and implementation of the developed strategy online to enhance the adaptability of relay coordination could be the focus of future research in this area. In addition, scholars can further explore the proposed hybrid combination executed in this study to further enhance the outcomes.

AUTHOR CONTRIBUTIONS

G. N. Obiora: Conceptualization, Supervision, Investigation, Validation, Writing – original draft, Writing – review & editing. **G. Abdulhamid:** Conceptualization, Formal analysis, Methodology, Software, Resources, Validation, Visualization. **G. O. Igbinosa, C. B. Fiemobebefa and O. A. Bamido:** Investigation, Writing – review & editing

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