Research Article

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Comparative Performance Analysis of Transit Search Optimization and Particle Swarm Optimization for Overcurrent Relay Coordination in Radial System

İbrahim Arslanoğlu[*a], Fatih Mehmet Nuroğlu[b], İsmail Hakkı Altaş[c]

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[a,*] Karadeniz Technical University, Faculty of Engineering, Department of Electrical and Electronics Engineering
61080- Trabzon, Türkiye
Orcid: 0000-0002-8213-8278
e mail: ibrahimarslanoglu@ktu.edu.tr

[b] Karadeniz Technical University, Faculty of Engineering, Department of Electrical and Electronics Engineering
61080- Trabzon, Türkiye
Orcid: 0000-0003-2530-8901
e mail: fmn@ktu.edu.tr

[c] Ostim Technical University, Faculty of Engineering, Department of Electrical and Electronics Engineering
06374- Ankara, Türkiye
Orcid: 0000-0001-9298-4091
e mail: ismailhakki.altas@ostimteknik.edu.tr

[*]Corresponding author: ibrahimarslanoglu@ktu.edu.tr

ABSTRACT

Protection systems are crucial for ensuring the continuity and reliability of power systems. Simulating the power system before its implementation helps improve protection strategies. This study examines the coordination of non-directional overcurrent relays in a three-bus power system modeled in the ETAP software. A three-phase short-circuit fault was applied, and load flow analysis, short-circuit analysis, and relay coordination graphs were generated. To minimize relay operating times, the widely used Particle Swarm Optimization (PSO) algorithm and the Transit Search Optimization (TSO) algorithm, which was applied to relay coordination for the first time, were utilized. The results indicate that TSO significantly reduced the total relay operating time compared to both PSO and the calculated values. The total operating time, initially 1.428 ms, was reduced by 19.82% to 1.145 ms using PSO, and further reduced by 46.43% to 0.765 ms using TSO. Additionally, a direct comparison of PSO and TSO revealed that TSO achieved a 33.19% greater reduction in relay operating time than PSO. These findings suggest that TSO may serve as a more effective optimization method for relay coordination compared to PSO.

Radyal Sistemde Aşırı Akım Rölesi Koordinasyonu için Geçiş Arama Optimizasyonu ve Parçacık Sürüsü Optimizasyonunun Karşılaştırmalı Performans Analizi

ÖZ

Koruma sistemleri, güç sistemlerinin sürekliliğini ve güvenilirliğini sağlamak için kritik öneme sahiptir. Güç sisteminin tesisinden önce simüle edilmesi, koruma stratejilerini iyileştirmeye yardımcı olur. Bu çalışmada, ETAP programında oluşturulan üç baralı bir güç sisteminde yönsüz aşırı akım rölelerinin koordinasyonu incelenmiştir. Üç faz kısa devre arızası uygulanarak yük akışı, kısa devre analizi ve röle koordinasyon grafikleri oluşturulmuştur. Rölelerin çalışma sürelerini en aza indirmek için, yaygın olarak kullanılan Parçacık Sürü Optimizasyonu (PSO) algoritması ile röle koordinasyonunda ilk kez uygulanan Transit Arama Optimizasyonu (TSO) algoritması kullanılmıştır. Elde edilen sonuçlara göre, TSO hem PSO'ya hem de hesaplanan değerlere kıyasla rölelerin toplam çalışma süresini önemli ölçüde azaltmıştır. Hesaplanan toplam süre 1.428 ms olup, PSO ile %19.82 oranında azaltılarak 1.145 ms'ye, TSO ile %46.43 oranında azaltılarak 0.765 ms'ye düşürülmüştür. Ayrıca, PSO ve TSO karşılaştırıldığında, TSO PSO'ya göre röle çalışma süresini %33.19 daha fazla azaltmıştır. Bu bulgular, röle koordinasyonunda TSO'nun PSO'ya kıyasla daha etkin bir optimizasyon yöntemi olabileceğini göstermektedir.

Anahtar Kelimeler: Aşırı akım röle koordinasyonu, Parçacık sürüsü optimizasyonu (PSO), Geçiş Arama Optimizasyonu (TSO), ETAP

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1. Introduction

The demand for electrical energy is steadily increasing. Therefore, the reliability of the power system and the continuity of energy supply are crucial at all stages, from generation to consumption. Ensuring reliability and continuity is heavily reliant on designing protection systems that align with operational conditions.

To prevent equipment damage and ensure stable operation during fault conditions, protective systems are essential in distribution networks. Faults often cause significant fluctuations in current levels within short-circuited areas. Devices like fuses and overcurrent relays react to these variations to safeguard the system. In radial distribution networks, non-directional overcurrent relays are widely preferred because they offer a cost-effective, straightforward, and dependable protection solution [1,2].

In power system design, operational safety must be prioritized under all conditions by accounting for worst-case scenarios and selecting appropriate equipment. Faults in the system are inevitable, leading to high fault currents that, if not promptly detected and cleared, can cause equipment damage and system instability. Protection systems are integral to ensuring reliable operation, minimizing outage durations, and maximizing power delivery efficiency within the distribution network [1].

Power systems are engineered to prevent harm to people, equipment, and property. This design is based on criteria such as speed, reliability, selectivity, cost-effectiveness, and ease of operation [3,4]. Protection equipment in power systems includes relays, which perform calculations using current and voltage data from measuring instruments; circuit breakers, which operate according to relay commands in the event of a fault; current and voltage transformers, which supply data to the relays; and auxiliary communication equipment.

The primary goal of protection in power systems is to maintain operation within specified voltage and current limits, isolate faulted sections during malfunctions, and prevent damage to equipment and harm to personnel. Due to the complexity of power systems, it is essential to model and simulate them in a virtual environment. This enables a comprehensive analysis of system behavior and facilitates the implementation of protection strategies for potential fault scenarios. As the number of overcurrent relays increases, coordinating their operation has become a major challenge, further complicated by various system constraints. Optimization techniques have proven effective in managing these challenges, significantly enhancing operational efficiency.

When examining the literature, numerous studies have focused on minimizing the total operating time of relays through overcurrent relay coordination in radial networks. In one study [5], relay coordination was performed using ETAP software, while in [6], the impact of integrating a solar power plant into a 13-bus test system on relay coordination was analyzed and resolved using ETAP. Additionally, in [7], an adaptive modified firefly algorithm (AMFA) was employed for relay coordination using both MATLAB and ETAP software. In [8], the time multiplier setting required for relay coordination was optimized using the Two-Phase Simplex and Particle Swarm Optimization (PSO) algorithms. These studies highlight the effectiveness of ETAP software in power system modeling and relay coordination analysis, demonstrating its capability to simulate fault scenarios and optimize protection settings with high accuracy.

Several studies have examined various optimization techniques to improve overcurrent relay coordination. In [9], a genetic algorithm was applied with a proposed objective function to optimize relay settings for radial and parallel feeders, effectively mitigating miscoordination between primary and backup relays. In [10], the Time Dial Setting (TDS) of overcurrent relays was optimized using the Cuckoo Search Algorithm (CSA) and compared with the Firefly Algorithm (FA), with ETAP simulations confirmed that CSA delivered superior and more reliable relay coordination. In [11], the Bozkurt Optimization Algorithm (BOA) was successfully applied to the IEEE 8-Bus test system, with a comprehensive performance analysis demonstrating its effectiveness. Furthermore, the study in [12] tackled the overcurrent relay coordination problem at the Hasançelebi transformer center using four different algorithms and found that the Whale Optimization Algorithm (WOA) delivered the fastest solutions.

These studies emphasize the effectiveness of metaheuristic optimization algorithms in enhancing the coordination of overcurrent relays. By employing advanced computational techniques, significant improvements in relay response time and overall protection system reliability can be achieved, thereby increasing the efficiency and robustness of power system protection.

In [13], the Path-Finder Algorithm (PFA) and Neural Network Algorithm (NNA) were applied for the first time to solve the overcurrent relay coordination problem. A performance analysis was conducted using three test cases with objective functions for both directional and non-directional relays. Research in [14] applied PSO to solve the overcurrent relay coordination problem. Similarly, the study in [15] applied PSO and the Crow Search Algorithm (CSA) to coordinate directional and non-directional relays in power system protection. Lastly, in [16], the Fidan Developmental Algorithm (FGA) and League Championship Algorithm (LCA) were employed for overcurrent relay coordination, yielding effective results. These studies highlight the diversity and effectiveness of metaheuristic approaches in addressing relay coordination challenges.

This study focuses on optimizing overcurrent relay coordination in power systems using both traditional and novel metaheuristic algorithms. A three-busbar power system model was simulated in the ETAP software, where load flow, short circuit analyses, and relay coordination graphs were developed. Particle Swarm Optimization (PSO) and the newly introduced Transit Search Optimization (TSO) Algorithm were applied to minimize relay operating times. The results demonstrated that the TSO algorithm outperformed PSO by significantly reducing total relay operating times, highlighting its potential as an effective optimization method for relay coordination.

The rest of this paper is organized as follows; Overcurrent relay coordination formulation for distribution networks, parameters of radial network and information about different optimization algorithms are given in Section II. Section III presents information about the application of the algorithms on sample test systems and a comparative analysis with other algorithms. Conclusions are discussed in Section IV.

2. Material and Method

2.1. Overcurrent protection

This section is prepared in accordance with the following IEEE standards: IEEE Guide for Protective Relay Applications to Distribution Lines (IEEE Std C37.230™-2020), IEEE Guide for Protective Relay Applications to Transmission Lines (IEEE Std C37.113™-2015), and IEEE Recommended Practice for System Grounding of Industrial and Commercial Power Systems (IEEE Std 3003.1-2019).

When a fault occurs in a power system, the fault current exceeds the current flowing under normal operating conditions. To protect the system, overcurrent relays are connected to the equipment. When the nominal current level is exceeded, an opening signal is sent to the breaker to prevent damage. The relationship between the current through the overcurrent relay and its operating current is expressed as the current–time (operating) characteristic. Based on this characteristic, relays can be configured to operate in either definite-time or inverse-time mode. Typically, inverse-time mode is used for phase-to-phase faults, while definite-time mode is preferred for phase-to-ground faults. Figure 1 illustrates the definite-time operating characteristic of an overcurrent relay. In definite-time mode, if the fault current exceeds the relay's set current (I>) threshold, the relay will trip after a specific delay (t>). However, regardless of the current level, the relay's opening time remains constant until the instantaneous trip (I>>) setting is reached. Once the instantaneous trip threshold (I>>) is reached, the relay activates immediately.

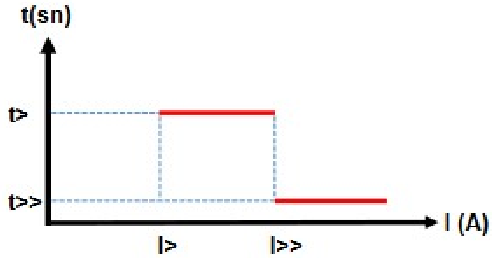

Figure 1. Definite-time operation characteristic

Figure 2 shows the inverse-time operation curve of the overcurrent relay. In inverse-time mode, when the set current threshold is exceeded, the relay's operating time decreases as the current level increases. This allows for quicker isolation of higher fault currents. Current-time curves depend on standard specifications, and Table 1 provides the coefficients for different inverse-time characteristics [3,17].

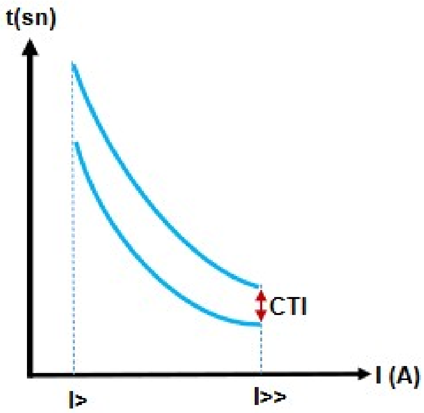

Figure 2. Inverse time operation characteristic

Table 1. Constants of curve types for the ANSI/ IEEE relay

Curve Type	Standard	A	B	P
Moderately Inverse	ANSI/IEEE	0.05	0.114	0.02
Very Inverse	ANSI/IEEE	19.61	0.491	2.00
Extremely Inverse	ANSI/IEEE	28.20	0.122	2.00

2.2. Selectivity and relay coordination

In a radial system, when multiple relays detect the same fault, the relay farthest from the source responds first, while the relay closer to the source operates later. This process is known as selectivity or selective operation. Configuring relays for selective operation is referred to as relay coordination. Figure 3 illustrates a simple radial distribution system, including a grid, transformer, line, three circuit breakers (CB1, CB2, CB3), three current transformers (CT1, CT2, CT3), three overcurrent relays (R1, R2, R3), and a load. When a fault occurs at point F, all three relays detect it. Since relay R3 is closest to the fault, it should ideally send a trip signal to circuit breaker CB3, isolating the fault at the third busbar to maintain power continuity for the rest of the system. If relay R3 fails to send a trip signal, relay R2 should then send a trip signal to breaker CB2. If relay R2 also fails, relay R1 would then operate, sending a trip signal to CB1 to isolate the faulty section from the system. A coordination time interval exists between the operating times of these relays; when calculating CTI, factors such as relay operating time, breaker operating time, and mechanical delays are also considered.

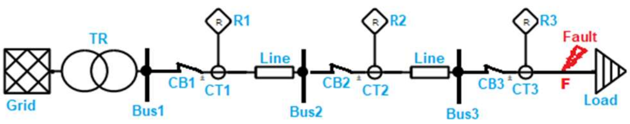

Figure 3. Radial distribution system relay coordination

2.3. Radial grid parameters

Table 2 presents the parameters of the radial grid. For phase-to-phase faults, the grid's overcurrent relays are coordinated using the standard inverse-time curve. As shown in Equation (1), generating this curve requires the pickup current (I_{Pickup}) and time dial setting (TDS) values. By optimizing these two parameters, the total operating time of the relays can be minimized [9,18,19].

Table 2. Grid parameters

Component	Teknik Özellikler
U1	Rated kV = 33
	X/R= 15
	10 MVA
T1	33/ 6 kV
	X/R= 10 %Z=8
	Cable 1: 10 km, XLPE CU 120 mm^2
Line	Cable 2: 5 km, XLPE CU 95 mm^2
	Cable 3: 3 km, XLPE CU 70 mm^2
Current	CT1, CT3, CT4: 300/1
Transformer	CT2: 1200/1
Circuit	CB1: 36 Kv 0.05 sec
Breaker	CB2, CB2, CB3: 7.2 Kv 0.05 sec
Relay	R1, R2, R3, R4: Typical overcurrent relay
	Lump 1: 2 MVA, 6 kV, (%80 Motor, %20 Static)
Load	Lump 2: 1 MVA, 6 kV, (%80 Motor, %20 Static)
	Lump 3: 2 MVA, 6 kV, (%80 Motor, %20 Static)

In order to perform the optimization process, the objective function is required. The objective function (OF) used in overcurrent relay coordination is presented in Equation (1).

$$OF = \sum_{1}^{n} T_{i,k} \cdot W_{i,k} \tag{1}$$

where n denotes total number of relays in the system, and W_i represents the weight coefficient. The weight coefficient is set to 1 because the probability of failure across different feeders in the network is equal, and the feeder distances are generally similar [3, 20, 21].

$$T_{i,k} = TDS_i x \frac{A}{\left(\frac{I_F}{I_{Pickup}}\right)^P - 1} + B \tag{2}$$

$T_{i,k}$ for phase fault at point k i. it represents the operating time of the relay. This value is calculated by Equation (2). where; TDS_i i. time setting of the relay; I_F the magnitude value of the fault current measured from the current relay; I_{Pickup} the set threshold current value of the overcurrent relay; the indices A, B and P refer to the constant coefficients given in Table 1, which vary depending on the overcurrent relay characteristic.

2.4. Constraints

There are some restrictions when performing overcurrent relay coordination. For example, in the inverse time curve given in figure 4, I_F operating time of the primary relay for fault current $T_{(i,k)p}$ and the operating time of the backup relay $T_{(i,k)b}$ can be determined as follows. The coordination constraint between the relays is given in equation (3). In addition, TDS setting constraints, I_{Pickup} setting constraints and operating time interval constraints are also needed. These constraints are given in Equation (4)-(6) respectively [2,17].

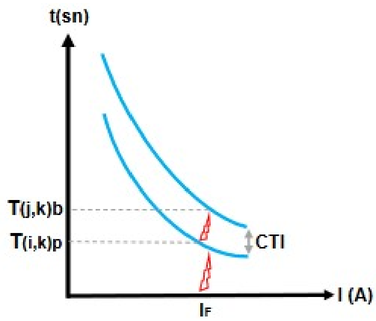

Figure 4. Inverse time curve

$$T_{(i,k)b} - T_{(j,k)p} \geq CTI \tag{3}$$

$$TDS_{(i)\min} \leq TDS_{(i)} \leq TDS_{(i)\max} \tag{4}$$

$$I_{Pickup_{(i)\min}} \leq I_{Pickup_{(i)}} \leq I_{Pickup_{(i)\max}} \tag{5}$$

$$TDS_{(i)\min} \leq TDS_{(i)} \leq TDS_{(i)\max} \tag{6}$$

2.5. Particle Swarm Optimization (PSO)

It is an algorithm developed based on the fact that the movements of certain animals moving in herds to find food influence other individuals. Each individual searching for a solution is called a particle, and the collection of these particles is known as a swarm. The basic outline of Particle Swarm Optimization (PSO) is as follows [22,23]:

Step 1: Initialize the population of particles
Step 2: Evaluate the objective function
Step 3: Update the particle solutions
Step 4: Check the stopping criteria
Step 5: Determine the optimal TDS value and I_{Pickup} based on these values, calculate the objective function

In this study, *TDS* and I_{Pickup} were determined according to Equation (7)-(9).

$$P_i^{k+1} = P_i^k + v_i^{k+1} \tag{7}$$

where, P_i^k represents the initial position of the particle; *k*, *k* + 1 represents the iteration number. Then, the velocity value (v) is updated to the position P_i^{k+1} .

$$v_i^{k+1} = w.v_i^k + c_1.rnd_1.(pbest_i - p_i^k) + c_2.rnd_2.(gbest - p_i^k) \tag{8}$$

where, *pbest* represents the best solution of the *ith* particle; *gbest* represents the best position of the swarm; c_1 and c_2 represent the weight coefficients; *w* represents the weight function; and rnd_1 and rnd_2 represent the random number generators that produce values between 0 and 1.

$$v_{max} = \frac{u_b}{l_b} \quad (9)$$

where, the speed value V_{max} is limited by the upper limit u_b and the lower limit l_b . The parameters of the PSO algorithm used in this study are presented in Table 3.

Table 3. PSO algorithm parameters

Number of Population	Number of iterations	c_1	c_2
20	60	2	2

2.5. Transit Search Optimization (TSO)

The Transit Search Optimization (TSO) algorithm is a novel astrophysics-inspired metaheuristic optimization technique. It is based on the "transit method" used in exoplanet discovery, where periodic reductions in a star's brightness indicate the presence of a transiting planet. TSO adapts this principle to solve optimization problems by balancing exploration and exploitation to find the optimal global solution. The TSO implementation is divided into five phases: galaxy, transit, planet, neighbor, and exploitation. Figure 5 represent the details of the TSO. [24,25].

TSO is particularly effective in handling complex and large-scale optimization problems where classical methods struggle. It has a wide range of applications in engineering, artificial intelligence, energy systems, and machine learning.

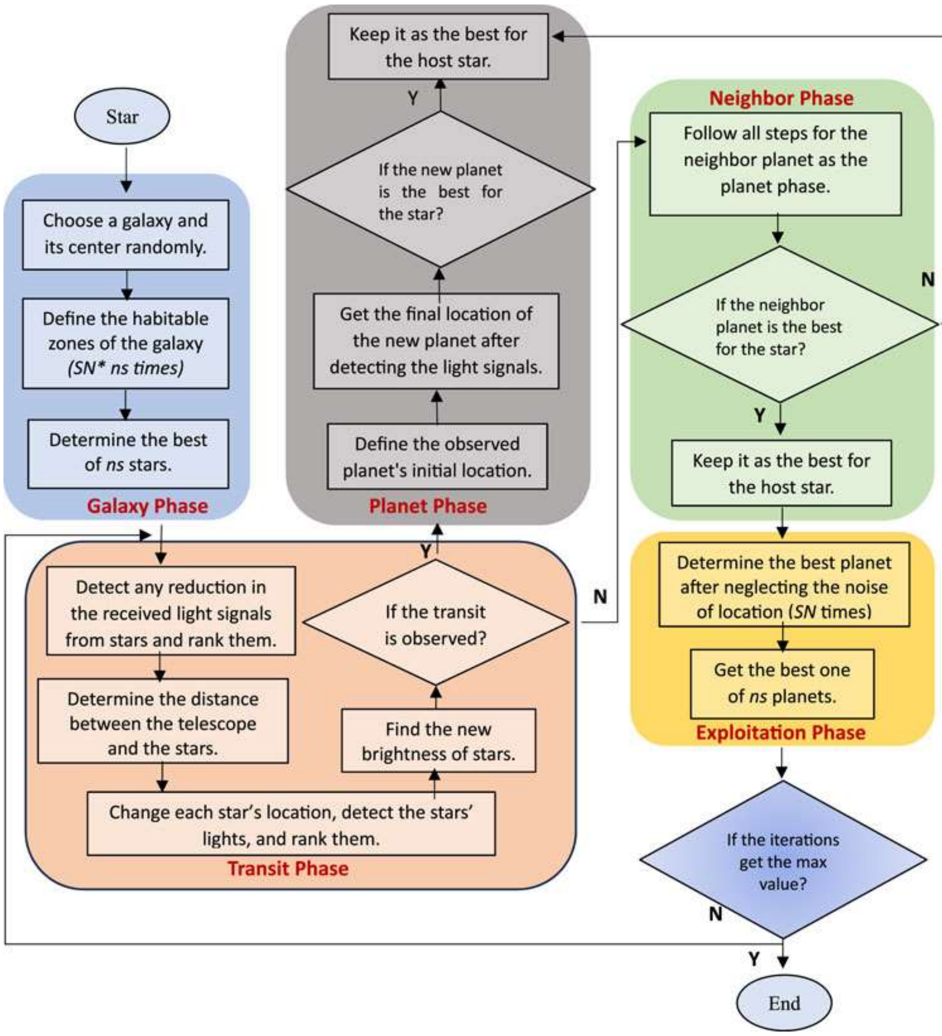

Figure 5. Flowchart of TSO algorithm

2.5.1. Fundamental steps of the TSO algorithm:

a. Galaxy Phase:

The algorithm begins by selecting a random galaxy center in the search space. The habitable zones within the galaxy are identified. Subsequently, the most promising regions with the highest potential are chosen for the next phase. The optimal locations for stellar systems, denoted as Ls (regions highly likely to host life), are illustrated in Figure 6. The locations of these regions are determined using Equations (10)-(12) as follows:

$$L_{R,I} = L_{Galaxy} + D - Noise \qquad I = 1,\ldots,(n_s x\ SN) \tag{10}$$

$$D = \begin{cases} c_1 L_{Galaxy} - L_r \\ c_1 L_{Galaxy} + L_r \end{cases} \ if \begin{cases} z = 1\ (Negative) \\ z = 1\ (Positive) \end{cases} \tag{11}$$

$$Noise = (c_2)^3 L_r \tag{12}$$

n_s : Number of host stars

SN :Signal-to-noise ratio

$L_{R,I}$: The fitness of the stellar system

L_R : The initial locations for the best regions of the stellar systems

L_{Galaxy} : The random location for the center region of the galaxy

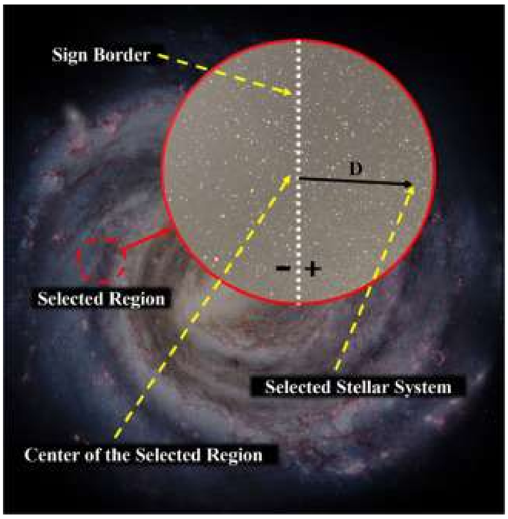

Figure 6. The selection process of the stellar systems by TSO

b. Transit phase:

The luminosity of stars is analyzed to detect potential transits. A decrease in the received light indicates the presence of a planet, allowing its location to be determined. If no transit is detected, the algorithm explores the best neighboring solutions. This phase is represented using Equations (13), (14) as follows:

$$Li = \frac{Ri/ns}{(di)^2} \qquad i = 1,\dots,ns \qquad Ri \in 1,\dots,ns \tag{13}$$

$$di = \sqrt{(Ls - Lt)^2} \tag{14}$$

Li : The luminosity and Ri, the rank of the star i are represented

di : The distance between the telescope and the star i.

Lt : The telescope's position (random)

c. Planet phase:

Planets corresponding to detected transits are identified, and their positions are refined by calculating distances from both the host star and the observer. Figure 7 shows a planet transiting between the star and the telescope. Figure 8 illustrates that, to account for the planet's orbital position in the TSO, three zones are defined and influenced by the application of the zone parameter (z) during the planet phase. This phase is represented using Equations (15)-(18) as shown below:

$$Lz = (C8LT + RL\ LS)/2i = 1,\dots,ns\ \&\ C8\ \ (random) = 0\ \ or\ 1$$

Lz :The initial location of the identified planet

$$\text{Lm,j} = \text{Lz} + \text{C9Lr if z(random)=1 j=1,...,SNC9(random)=-1 or 1 Aphelion region} \tag{15}$$

$$\text{Lm,j} = \text{Lz} + \text{c9Lr if z(random)} = 2\ \text{j=1,.., SNC9 (random)} = \text{-1 or 1 Perihelion region} \tag{16}$$

$$\text{Lm, j} = \text{Lz} + \text{c10Lr if } z(\text{random}) = 3 \; j = 1, \ldots, \text{SN C9 (random)} = -1 \text{ or } 1 \text{ Neutral region} \tag{17}$$

$$Lp = \frac{\sum_{j=1}^{SN} Lm, j}{SN} \tag{18}$$

Lp: The detected planet's final location

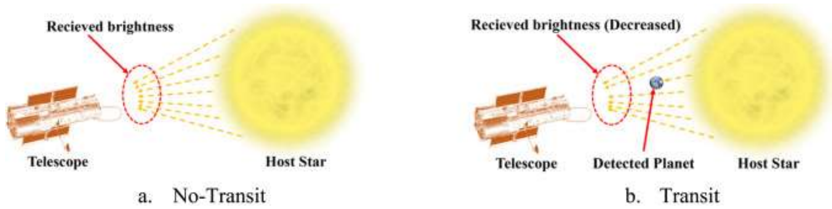

Figure 7. Transit observed by the space telescope

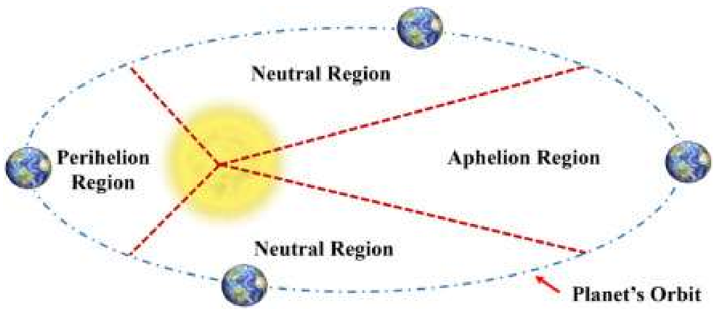

Figure 8. A planet's orbit around a star and the corresponding zones in the algorithm.

d. Neighbore phase:

If no transit is observed, the algorithm examines nearby candidate solutions surrounding the previously detected best solution. If a superior solution is identified, it replaces the previous one.

e. Exploitation phase:

The properties of detected planets (such as density, atmospheric composition, and habitability conditions) are assessed. Additional information is integrated to further refine planetary characteristics. The optimal overall solution is determined, thereby concluding the optimization process. This phase is represented using Equations (19)-(22) as follows:

$$\text{LE, j} = \text{C16 Lp} + \text{C15K, if Ck} = 1 \text{ (State 1)} \tag{19}$$

$$\text{LE, j} = \text{C16 Lp} + \text{C15K, if Ck} = 2 \text{ (State 2)} \tag{20}$$

$$\text{LE, j} = \text{Lp} + \text{C15K, if Ck} = 3 \text{ (State 3)} \tag{21}$$

$$\text{LE, j} = \text{Lp} + \text{C15K, if Ck} = 4 \text{ (State 4)} \tag{22}$$

C15 (a random number) = [0,2]; C16 (a random number) = [0,1]; K = (C17)p Lr, C17 (a random vector) = [0,1]; P (a random power) = [1...., SN]. LE: represents the characteristics of the planet

The phases of the proposed algorithm, along with their definitions and details, have been presented. To more clearly illustrate the implementation process of the TSO, a general pseudocode is provided in Algorithm 1 [24].

Algorithm 1. General pseudocode of the TSO algorithm

```
Inputs:
  Number of host stars n_s; Signal-to-noise ratio SN; The number of iterations n_It
Outputs:
  Location of the best planet ever L_B and its corresponded fitness f_B
Initialization:
  The initial location of the galaxy
do Galaxy phase using Algorithm 1
Return the Best Stars, L_S
While (Stopping condition is not met) do
  do Transit Phase using Algorithm 2
    for i = 1:n_s
      if transit is detected
        do Planet Phase using Algorithm 3
       else
        do Neighbor Phase using Algorithm 4
      end
    end
   Return L_P,i and its corresponded fitness (f_P,i) for each star
  do Exploitation Phase using Algorithm 5
     Return L_P and its corresponded fitness (f_P,i) for each star
end
Return L_B and its corresponded fitness (f_B)
```

3. Modeling and Analysis of The Grid

A radial grid model was developed using the ETAP software environment, incorporating the parameters specified in Table 2. The relay coordination curve was generated by performing load flow and short circuit analyses, combined with calculations based on outcomes derived from both the Particle Swarm Optimization (PSO) and Transit Search Optimization (TSO) algorithms.

Figure 9 presents the load flow analysis results, while Figure 10 illustrates the short circuit analysis. Figure 11 depicts the selectivity and relay coordination, and Figure 12 shows the calculated relay coordination curve. Figure 13 highlights the overcurrent relay coordination achieved using the PSO algorithm, whereas Figure 14 highlights the overcurrent relay coordination utilizing the TSO algorithm. Figure 15 presents the optimal objective function value obtained with both PSO and TSO. Additionally, Table 4 summarizes the relay isolation times for the three-phase fault and the total isolation time of the relays.

Table 4. Operating times of relays

	I_{FAULT} (kA)	Calculated Relay Time ms	PSO Relay Time ms	TSO Relay Time ms
R1	0.262	863	665	367
R2	1.405	381	359	236
R3	1.812	120	66	88
R4	2.179	64	55	74
Total Time		1.428	1.145	765

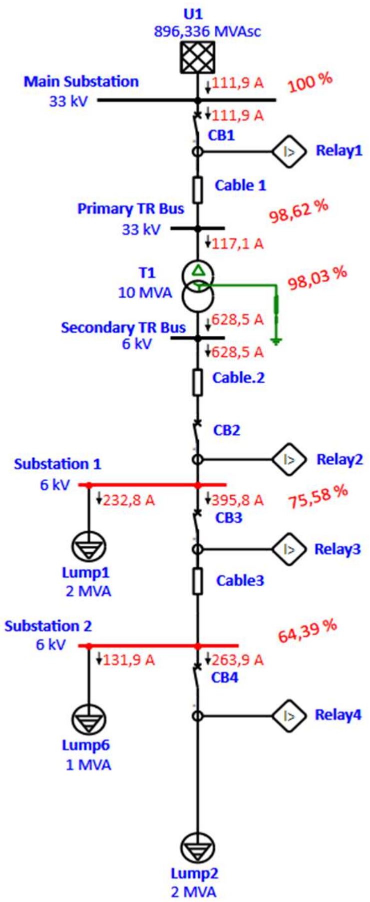

Figure 9. Load flow analysis

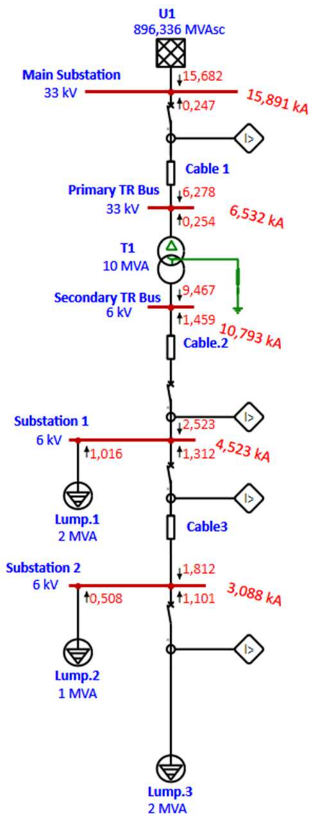

Figure 10. Short circuit analysis

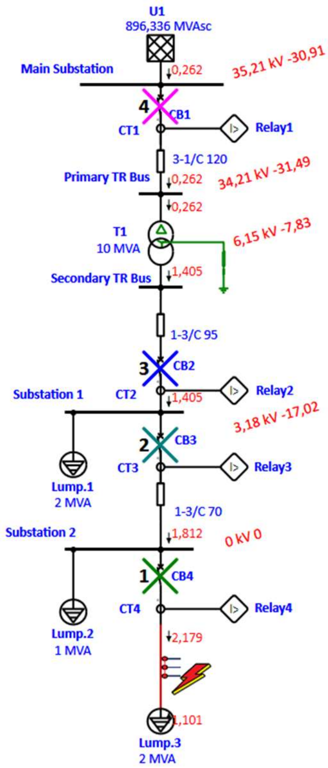

Figure 11. Selectivity and relay coordination

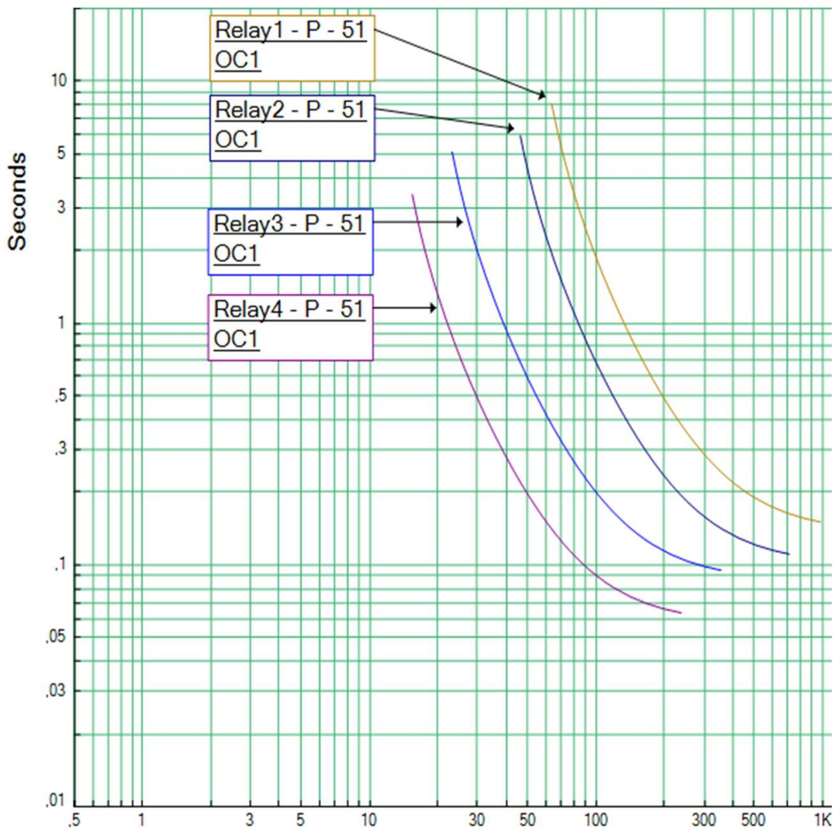

Figure 12. Calculated relay coordination

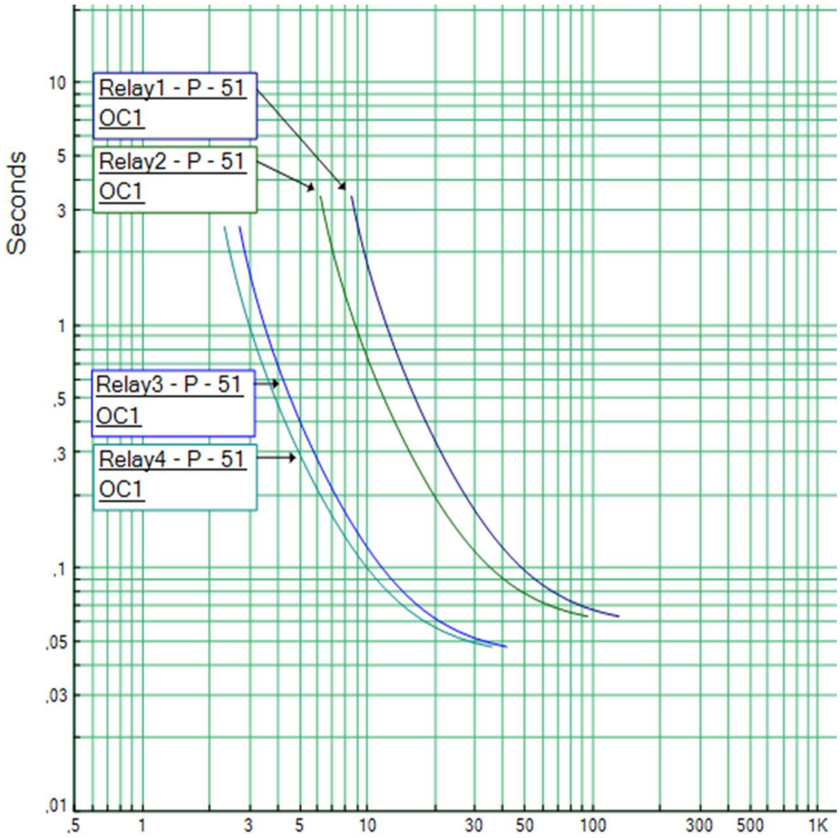

Figure 13. Overcurrent relay coordination using PSO algorithm

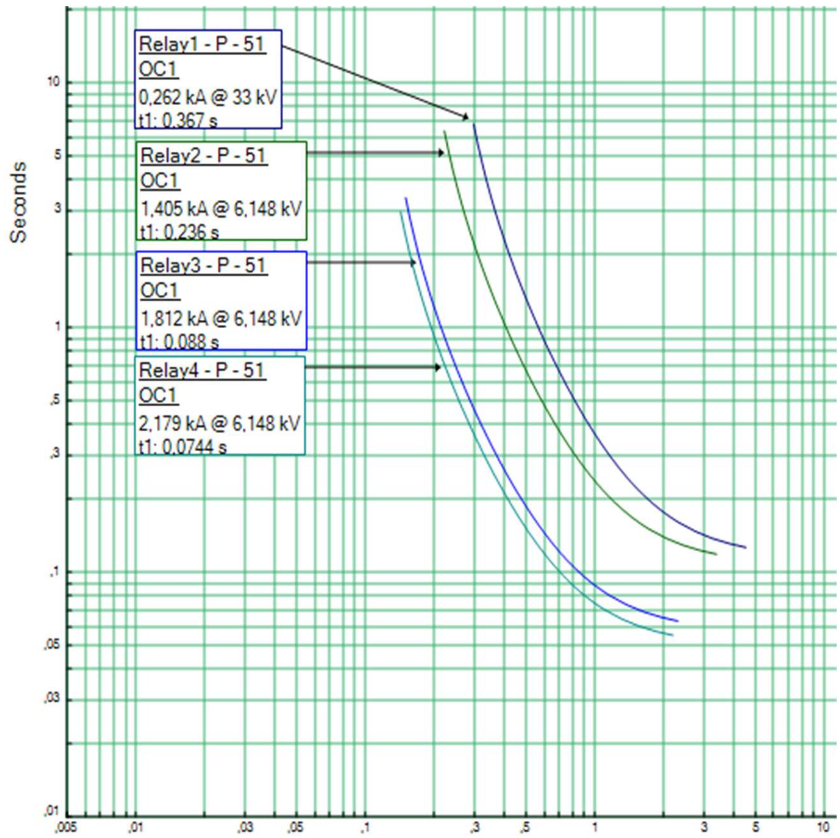

Figure 14. Overcurrent relay coordination using TSO algorithm

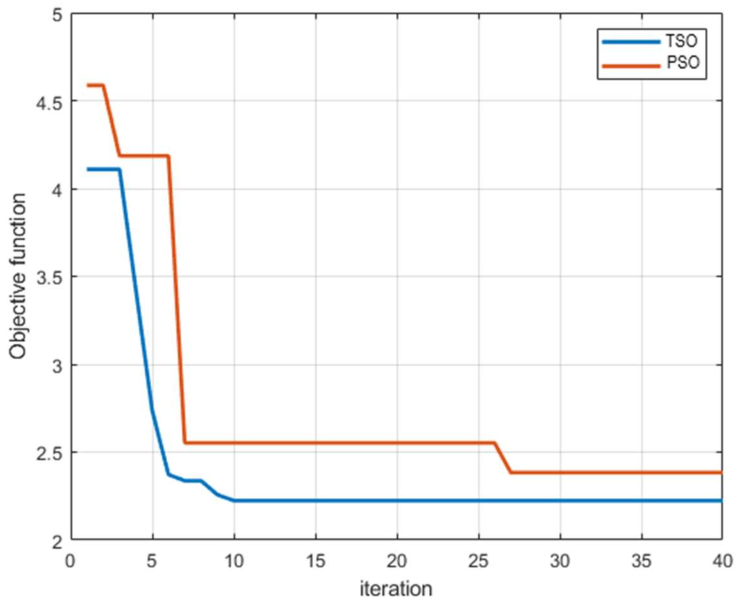

Figure 15. Best value of the objective function with PSO and TSO

4. Conclusion

This study aimed to optimize overcurrent relay coordination to enhance protection reliability and reduce the total operating time in power systems. A three-busbar power system model was developed in ETAP, where load flow analysis, short-circuit analysis, and relay coordination evaluations were performed in accordance with industry standards and regulatory requirements. An efficient and reliable protection scheme is critical for minimizing the adverse effects of faults on system stability and equipment longevity.

To achieve this, two metaheuristic algorithms (PSO, TSO) were employed to optimize relay settings. The initial total operating time of the relays was calculated as 1.428 milliseconds, which was significantly reduced through optimization. With the PSO algorithm, this value improved to 1.145 milliseconds, yielding a 19.81% reduction in total relay operating time. The newly implemented TSO algorithm provided even better results, achieving further reductions and reaching a total operating time of 0.765 milliseconds, representing a 46.42% improvement compared to the initial value. Additionally, TSO outperformed PSO by reducing the relay operating time by 33.19%. These results underscore the capability of advanced metaheuristic techniques in minimizing fault clearance times, thereby enhancing system resilience and operational efficiency.

The findings indicate that metaheuristic algorithms can play a vital role in optimizing relay settings, enabling adaptive, fast, and reliable protection schemes in complex power networks. In particular, the first-time application of the TSO algorithm in relay coordination has shown promising results, suggesting its potential as an alternative to traditional methods. Given the increasing complexity of power systems with distributed generation and dynamic network configurations, future studies should explore hybrid optimization approaches and real-time adaptive relay coordination techniques. Furthermore, additional investigations using larger test systems and incorporating renewable energy sources could evaluate the adaptability of these algorithms under varying fault conditions.

In conclusion, this study contributes to the ongoing research on overcurrent relay coordination by providing a comparative analysis of both established and novel optimization techniques. The successful implementation of TSO, along with its superior performance over PSO, highlights the importance of exploring new computational intelligence methods to improve protection system efficiency. Future research may extend this work by integrating other metaheuristic approaches, such as artificial neural networks and hybrid optimization frameworks, to further enhance relay coordination and overall system protection reliability.

Conflict of Interest Statement

The authors declare that there is no conflict of interest

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