Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

GU J Sci, Part C, 13(2): 417-430 (2025)

Optimal Coordination of Directional Overcurrent Relays Using an Exponential-Based Non-Standard Characteristic and the Nutcracker Optimizer

Alisan AYVAZ[1*]

[1]Amasya University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Amasya, Türkiye

Article Info

Research article
Received: 02/01/2025
Revision: 06/03/2025
Accepted: 21/03/2025

Keywords

Optimal coordination
Directional overcurrent relays
Non-standard characteristic
Nutcracker optimizer

Makale Bilgisi

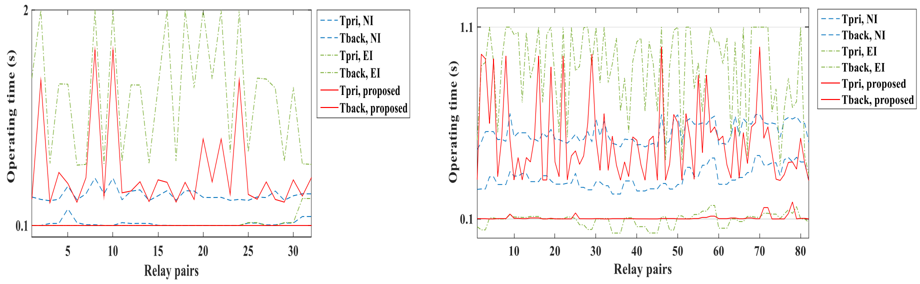
Araştırma makalesi
Başvuru: 02/01/2025
Düzeltme: 06/03/2025
Kabul: 21/03/2025

Anahtar Kelimeler

Optimal koordinasyon
Yönlü aşırı akım koruma röleleri
Standart olmayan karakteristik
Fındıkkıran kuşu optimize edicisi

Graphical/Tabular Abstract (Grafik Özet)

This paper proposes the use of an exponential-based non-standard relay characteristic curve for the optimal coordination of directional overcurrent protection relays and employs the Nutcracker Optimizer (NOA) to solve the optimization problem. / Bu makale, yönlü aşırı akım koruma rölelerinin optimal koordinasyonunda bir üstel tabanlı standard olmayan röle karakteristik eğrisinin kullanımını ve optimizasyon probleminin çözümünde fındık kıran kuşu optimize edicisi kullanımını önermektedir.



(a) *(b)*

Figure A*: Primary and backup relay operating times obtained via NOA algorithm for a) IEEE 9-bus and b) IEEE 15-bus systems /**Şekil A:**. NOA algoritmasıyla elde edilen a) IEEE 9-baralı ve b) IEEE 15-baralı sistemler için birincil ve yedek röle çalışma süreleri*

Highlights (Önemli noktalar)

- *The use of an exponential-based relay characteristic type for the optimal coordination of DOCRs is proposed.*
- *The recently developed NOA algorithm is proposed for solving the optimal coordination problem.*
- *The proposed method is tested on the IEEE 9-bus and IEEE 15-bus test systems.*

Aim (Amaç): *Providing a more selective and faster protection coordination by reducing relay operating times. / Röle işlem sürelerinin düşürülerek daha seçici ve hızlı bir koruma koordinasyonunun sağlanması.*

Originality (Özgünlük): *This study proposes a new exponential-based non-standard relay characteristic curve and the use of the recently developed population-based metaheuristic method, the Nutcracker Optimizer, for the optimal coordination of directional overcurrent protection relays. / Bu çalışmada yeni bir üstel tabanlı standard olmayan röle karakteristik eğrisi ve yönlü aşırı akım koruma rölelerinin optimal koordinasyonunda son zamanlarda geliştirilmiş olan bir popülasyon bazlı metasezgisel yöntem olan fındık kıran kuşu optimize edicisi kullanımını önerilmektedir.*

Results (Bulgular): *The results show that the use of either the NOA algorithm or the proposed relay characteristic individually provides effective outcomes; however, their combined use significantly reduces the total relay operating time. / Sonuçlar, NOA algoritmasının veya önerilen röle karakteristiğinin ayrı ayrı olarak kullanımının sonuçlarda etkililik sağladığını, fakat birlikte kullanımı ile toplam röle işlem süresinin önemli ölçüde azaldığını göstermiştir.*

Conclusion (Sonuç): *The proposed method is a powerful alternative approach for solving the optimal coordination problem of DOCRs. / Önerilen yöntem, DOCR'ların optimal koordinasyon problemini çözmek için güçlü bir alternatif yaklaşımdır.*

*Corresponding author, e-mail: alisan.ayvaz@amasya.edu.tr
DOI: 10.29109/gujsc.1612191

GU J Sci, Part C, 13(2): 417-430 (2025)

Gazi Üniversitesi
Fen Bilimleri Dergisi
PART C: TASARIM VE TEKNOLOJİ

Gazi University
Journal of Science
PART C: DESIGN AND TECHNOLOGY

http://dergipark.gov.tr/gujsc

Optimal Coordination of Directional Overcurrent Relays Using an Exponential-Based Non-Standard Characteristic and the Nutcracker Optimizer

Alisan AYVAZ[1*]

[1]*Amasya University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Amasya, Türkiye*

Article Info

Research article
Received: 02/01/2025
Revision: 06/03/2025
Accepted: 21/03/2025

Keywords

Optimal coordination
Directional overcurrent relays
Non-standard characteristic
Nutcracker optimizer

Abstract

Directional overcurrent relays (DOCRs) play a crucial role in protecting sub-transmission and distribution systems due to their simplicity and cost-effectiveness. For selective and rapid protection, proper coordination of these relays is essential. At this point, the coordination of DOCRs is formulated as an optimization problem. The primary objective of this problem is to minimize relay operating times without violating coordination constraints. However, considering the complex nature of power systems, solving this nonlinear problem with high-level constraints becomes challenging. Furthermore, achieving efficiency in such solutions using standard relay characteristics is also difficult under the presence of numerous coordination constraints. In this context, this study proposes the use of an exponential-based non-standard relay characteristic function for calculating relay operating times and employs the nutcracker optimizer, a recently developed metaheuristic optimization algorithm, for solving the problem. The performance of the proposed method is tested on the IEEE 9-bus and IEEE 15-bus test systems, which are widely used in this field. The results obtained with the proposed method are compared with those in the literature and show the effectiveness of the proposed approach. Especially, the results demonstrate that the exponential-based non-standard relay characteristic used in the proposed method achieves approximately a 67% reduction in relay operating times compared to the standard relay characteristic (normally inverse) for the IEEE 15-bus system.

Yönlü Aşırı Akım Koruma Rölelerinin Üstel Tabanlı Standart Olmayan Karakteristik ve Fındıkkıran Kuşu Optimize Edicisi Kullanılarak Optimal Koordinasyonu

Makale Bilgisi

Araştırma makalesi
Başvuru: 02/01/2025
Düzeltme: 06/03/2025
Kabul: 21/03/2025

Anahtar Kelimeler

Optimal koordinasyon
Yönlü aşırı akım koruma röleleri
Standart olmayan karakteristik
Fındıkkıran kuşu optimize edicisi

Öz

Yönlü aşırı akım koruma röleleri (YAAKR), alt iletim ve dağıtım sistemlerinin korunmasında basit ve ekonomik oluşları dolayısıyla önemli bir rol oynamaktadırlar. Seçici ve hızlı bir koruma için bu rölelerin doğru bir şekilde koordine edilmesine ihtiyaç vardır. Bu noktada, Yakar'larına koordinasyonu bir optimizasyon problem olarak tasarlanmaktadır. Bu problemin temel amacı, röle işlem sürelerinin koordinasyon kısıtlarında bir ihlale yol açmadan minimize edilmesidir. Fakat güç sistemlerinin kompleks yapısı göz önüne alındığında bu yüksek seviyede kısıtlar içerebilen ve lineer olmayan problemi çözmek zor bir hal alabilmektedir. Buna ek, yüksek sayıda koordinasyon kısıtların varlığı altında standart röle karakteristikleri ile bu çözümde verim elde etmek de zor olabilmektedir. Bu kapsamda, bu çalışma röle işlem sürelerinin hesaplanmasında üstel tabanlı standart olmayan bir röle karakteristik fonksiyonunun ve problemin çözümünde son zamanlarda geliştirilen bir metasezgisel optimizasyon algoritması olan fındıkkıran kuşu optimize edicisinin kullanımını önermektedir. Önerilen yöntemin performansı, bu alanda sıklıkla kullanılan IEEE 9-bara ve IEEE 15-bara güç sistemleri üzerinde test edilmiştir. Önerilen yöntemle elde edilen sonuçlar, literatürdeki sonuçlarla karşılaştırılmış ve önerilen yöntemin etkililiği doğrulanmıştır. Özellikle, sonuçlar, önerilen çalışma kapsamında kullanılan üstel tabanlı standart olmayan röle karakteristiğinin 15-bara güç sistemi için röle işlem sürelerinde standart röle karakteristiği (normal ters zamanlı) kullanımına göre yaklaşık olarak %67 civarında azalma sağladığını göstermiştir.

*Corresponding author, e-mail: alisan.ayvaz@amasya.edu.tr
DOI: 10.29109/gujsc.1612191

1. INTRODUCTION (GİRİŞ)

The increasing demand for electricity, expansion of power grids, shift towards renewable energy generation, and technological advancements have significantly complicated power system-related problems, necessitating the development of innovative solutions. Within this scope, the coordination of directional overcurrent relays (DOCRs) emerges as one of these challenging problems. Given the expanding and increasingly complex nature of power systems, achieving fast and selective coordination among relays is of utmost importance. Fast coordination reduces stress on power system equipment and minimizes potential damage caused by faults, while selective coordination prevents unnecessary power outages in unaffected areas. Indeed, recent studies reveal a growing focus on this topic. Some of these studies propose improvements in optimization techniques, while others emphasize modifications in relay characteristics to achieve faster coordination. Examples of studies focusing on optimization techniques for solving the DOCR optimal coordination problem include the use of algorithms such as the enhanced white shark optimizer (EWSO) [1], modified electromagnetic field optimization algorithm (MEFO) [2], improved seagull optimization algorithm (ISOA) [3], sine cosine algorithm (SCA) [4], enhanced grey wolf optimizer (EGWO) [5], imperialistic competition algorithm (ICA) [6], modified evaporation rate water cycle algorithm (MERWCA) [7], and hybrid harris hawks optimization with sequential quadratic programming (HHO-SQP) [8].

The choice of optimization method is crucial for optimal coordination studies. The optimal coordination of DOCRs represents a nonlinear optimization problem with numerous constraints. Addressing this complex problem requires the application of effective optimization techniques. Moreover, depending on the size and structure of the power system, solving the protection coordination problem becomes even more challenging. Metaheuristic optimization methods demonstrate higher effectiveness compared to other classes of optimization approaches, such as mathematical programming methods, in solving complex problems like the optimal coordination problem [9]. In this context, a well-developed metaheuristic method always offers significant potential for solving the optimal coordination problem.

In studies in the literature, the normal inverse relay characteristic specified in IEC standards is generally used. In addition to the normal inverse characteristic, IEC standards also include other relay characteristics such as very inverse, extremely inverse, and long-time inverse, which can yield shorter relay operating times when employed [10]. Accordingly, in Reference [11], the selection of characteristic types based on various standards is considered as an optimization decision variable for relays. Similarly, in Reference [12], relay characteristics are determined through optimization by considering different characteristics. However, the selection of these standard characteristics does not always lead to effective results.

In recent years, advancements in relay technology and the increasing popularity of numerical relays in power system protection have been increasingly considered in the literature. Compared to electromechanical relays, numerical relays provide flexibility in relay characteristics, enabling the achievement of shorter relay operating times. In this context, with the flexibility offered by numerical relays, non-standard relay characteristics can also be assigned to DOCRs. Looking at the relevant studies in the literature, Reference [13] proposes a relay characteristic that includes voltage information, which is also utilized in Reference [14]. Similarly, Reference [15] introduces a two-level relay characteristic that allows assigning different characteristics for primary and backup operations of relays, resulting in shorter relay operating times while avoiding coordination time violations. In Reference [16], a user-defined relay characteristic is proposed. Instead of considering the coefficients related to the characteristic in the traditional relay operating time equation as fixed, the study in [16] treats them as continuous decision variables, enabling shorter relay operating times.

As observed, innovations in relay characteristics continue, and with the further proliferation of numerical relays, it is anticipated that studies on this topic will increase. In this context, this study proposes an exponential-based relay characteristic for DOCRs, aiming to achieve shorter relay operating times compared to traditional relay characteristics. The proposed relay characteristic provides significant reductions in relay operating times by offering flexibility in avoiding coordination constraints. While doing so, unlike the non-standard relay characteristics mentioned above, such as those in References [13] and [14], the proposed characteristic does not require an additional voltage input alongside the current information. On the other hand, although References [15] and [16] propose non-standard relay characteristics, they are fundamentally based on the conventional relay operating time calculation function standardized by the IEC. However, despite the flexibility provided in the coefficients related to relay characteristics within this conventional function, its effectiveness in terms of selectivity and speed remains debatable. Accordingly, this study proposes an exponential function instead of the conventional function used for relay operating time calculation to overcome the limitations of the conventional approach.

On the other hand, this study proposes the use of the nutcracker optimizer algorithm (NOA), developed in 2023 by Abdel-Basset et al. [17], for solving the optimal coordination problem of DOCRs. The NOA algorithm is a population-based metaheuristic optimization method inspired by the foraging, storing, and gathering behaviors of the nutcracker bird in nature. With advantages such as a small number of control parameters, fast computation, and robust global search capability, the NOA algorithm has demonstrated effective performance in solving various engineering problems, including photovoltaic model parameter extraction [18] and fresh agricultural product distribution [19].

The main contributions of this study can be summarized as follows:

• The use of an exponential-based relay characteristic type for the optimal coordination of DOCRs is proposed.

• The recently developed NOA algorithm is proposed for solving the optimal coordination problem.

• The proposed method is tested on the IEEE 9-bus and IEEE 15-bus test systems.

• Analyses are conducted under two different scenarios for the separate use of traditional relay characteristics and the proposed characteristic for DOCRs.

• The results obtained with the proposed method are compared with those in the literature, demonstrating the effectiveness of the proposed approach.

The remainder of this study is organized as follows: Section 2 presents the problem model for the optimal coordination of DOCRs. The mathematical model of the NOA algorithm is introduced in Section 3. Results and discussions are provided in Section 4. Finally, conclusions are presented in Section 5.

2. PROBLEM FORMULATION OF OPTIMAL COORDINATION OF DOCRS (YÖNLÜ AŞIRI AKIM KORUMA RÖLELERİNİN OPTİMAL KOORDİNASYONU PROBLEM FORMÜLASYONU)

In this section, the optimal coordination problem model is presented for both the scenarios of the use of traditional and proposed relay characteristics.

2.1. Problem Model For Conventional Relay Characteristic (Geleneksel Röle Karakteristiği İçin Problem Modeli)

In the optimal coordination problem of directional overcurrent relays (DOCRs), the objective is to minimize the total operating times of primary relays without violating coordination and relay coordination constraints. In this context, the relay setting parameters constitute the decision variables of the problem. The relay operating time, which depends on the relay setting parameters and the fault current passing through the relays, is determined as follows:

$$T_i = \frac{\mathrm{TDS}_i \times \alpha}{\left({I_{f_i}}/{\mathrm{PS}_i}\right)^{\beta} - 1} \tag{1}$$

where T_i represents the operating time of ith DOCR; I_{f_i} denotes the fault current passing through the relay i; TDS_i is the time dial setting of relay i; PS_i is the pickup setting of relay i; and α and β are constants related to the relay characteristic in IEC standards.

In the optimization process, while determining the relay operating times using Eq. (1), the coordination time interval (CTI) constraint must not be violated to ensure selective protection coordination. The constraint ensuring the preservation of the CTI between each pair of relays is as follows:

$$\mathrm{CTI}_{\mathrm{min}} \le T_{j,b} - T_{i,p} \tag{2}$$

where $T_{j,b}$ is the operating time of the backup relay j; $T_{i,p}$ is the operating time of the primary relay i; and $\mathrm{CTI}_{\mathrm{min}}$ represents the minimum value of coordination time interval.

Additionally, the relay setting parameters and relay operating times are constrained to specific ranges. The corresponding problem constraints are expressed by the following equations:

$$\mathrm{TDS}^{\mathrm{min}} \le \mathrm{TDS}_i \le \mathrm{TDS}^{\mathrm{max}} \tag{3}$$

$$\mathrm{PS}^{\min} \leq \mathrm{PS}_i \leq \mathrm{PS}^{\max} \quad (4)$$

$$T^{\min} \leq T_i \leq T^{\max} \quad (5)$$

The objective function of the problem, subject to the constraints provided above, is as follows:

$$\mathrm{OF} = \sum_{i=1}^{N_R} T_{i,p} + \mathrm{Penalty} \quad (6)$$

where N_R is the number of relays, and the Penalty is a function to penalize the constraint violations as follows:

$$\mathrm{Penalty} = \sum_{i=1}^{N_{RP}} \tau\times\max\left(\mathrm{CTI}_{\min} - T_{j,b} + T_{i,p}, 0\right) + \sum_{i=1}^{N_R} \tau\times[\max(T^{\min} - T_i, 0) + \max(T_i - T^{\max}, 0)] \quad (7)$$

where N_{RP} is the number of relay pairs, and τ equals 1000.

2.2. The Proposed Exponential-Based Characteristic (Önerilen Üstel Tabanlı Karakteristik)

The relay operating time function, defined by Eq. (1) and specified in IEC standards, varies based on the relay characteristics determined by the parameters α and "β" . However, the reduction of relay operating times is often limited by changing these characteristic parameters. To address this limitation, modifications to the function or the introduction of newly defined functions or curves can help overcome this constraint. Accordingly, this study proposes the use of an exponential-based relay characteristic function, defined by Eq. (8), as a replacement for the function given in Eq. (1). This approach aims to achieve shorter operating times for primary relays.

$$T_i = \left[\gamma_i \times \exp\left[\frac{\rho_i \times \mathrm{TDS}_i}{{I_{f_i}}/{\mathrm{PS}_i} - 1}\right]\right]^{\mu_i} \quad (8)$$

where γ_i, μ_i and ρ_i represent the relay characteristic parameters for relay i, which, similar to TDS_i and PS_i, are to be determined through the optimization process.

By utilizing the proposed exponential-based characteristic, the optimization results for each relay include a total of five different optimization decision variables or relay setting parameters, as given in Eq. (9).

$$X_i = [\mathrm{TDS}_i \quad \mathrm{PS}_i \quad \rho_i \quad \gamma_i \quad \mu_i] \quad (9)$$

The objective function of the proposed coordination problem becomes Eq. (6) subjected to Eqs. (2)-(5), (8).

To demonstrate the flexibility of the proposed exponential-based characteristic, an example plot of curves for the standard NI and EI relay characteristics with the proposed one is given in Figure 1.

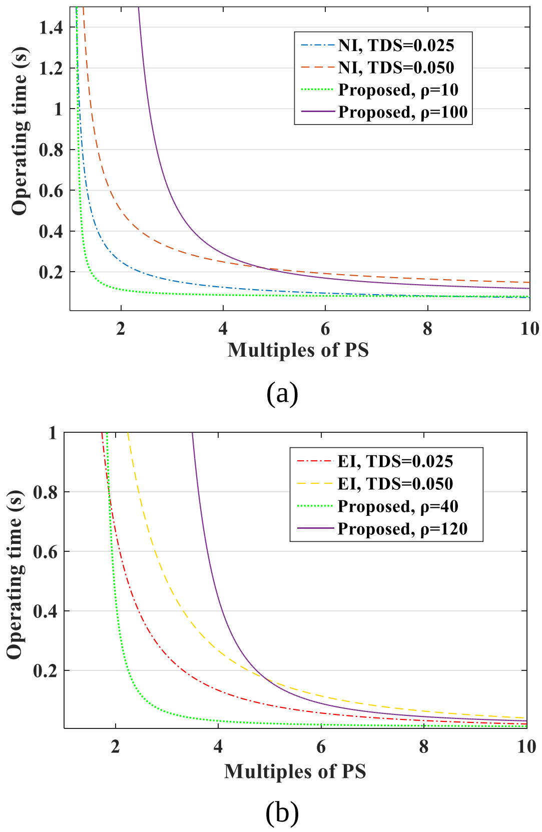


Figure 1. Comparison of the (a) NI-proposed and (b) EI-proposed relay characteristics ((a) NI-önerilen ve (b) EI-önerilen röle karakteristiklerinin karşılaştırılması)

Examining Figure 1 reveals that the proposed exponential-based characteristic provides greater flexibility over a wider range of fault currents. This flexibility is particularly beneficial for backup protection, as it helps prevent coordination constraint violations. Moreover, compared to standard relay characteristics, it achieves this by causing a lower increase in primary relay operating time at higher pickup current multiples, which correspond to primary protection.

3. THE NUTCRACKER OPTIMIZER ALGORITHM (FINDIKKIRAN KUŞU OPTİMİZE EDİCİSİ ALGORİTMASI)

The nutcracker optimization algorithm (NOA) is inspired by the food searching, storing, and retrieval behaviors of the Clark's nutcracker [17]. These birds exhibit two distinct behaviors during different seasons. During the summer and fall months, they focus on finding food, particularly high-quality seeds, and storing them in safe locations. In winter and spring, they retrieve the stored food to feed themselves and their young, ensuring survival. The birds' exceptional memory and survival behaviors are mathematically modeled in the NOA algorithm. This algorithm features two distinct exploration and exploitation phases mirroring the birds' seasonal behaviors.

In the first exploration phase, the birds search for food, aiming to find the best quality seeds. Their primary food source is the seeds within pinecones, and they typically prefer large seeds with higher nutritional value. If they do not find seeds that meet their preference, they continue searching. The behavior corresponding to the first exploration phase of the NOA algorithm is represented as follows:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^{t}, & if\ \tau_1 < \tau_2 \\ \begin{cases} X_{m,j}^{t} + \varepsilon \cdot \left(X_{A,j}^{t} - X_{B,j}^{t}\right) \\ \quad +\omega \cdot \left(r^2 \cdot U_j - L_j\right), & if\ t \le it^{max}/2 \\ X_{m,j}^{t} + \varepsilon \cdot \left(X_{A,j}^{t} - X_{B,j}^{t}\right) \\ \quad +\omega \cdot (r_1 < \delta) \cdot \left(r^2 \cdot U_j - L_j\right), & otherwise \end{cases} \end{cases} \quad (10)$$

where $X_{i,j}^{t}$ and $X_{i,j}^{t+1}$ are the current and the new positions of the ith nutcracker, respectively; $X_{A,j}^{t}$, and $X_{B,j}^{t}$ are the random nutcracker positions; $X_{m,j}^{t}$ denotes the mean of the dimension j for all nutcracker positions; U_j and L_j are upper and lower bound of the dimension j, respectively; r, r_1, τ_1, and τ_2 are random numbers between 0 and 1; it^{max} represents the maximum number of iterations; ε is a random number determined via the levy flight; δ is an algorithm parameter that controls avoiding from local optima; and ω is defined by the following equation:

$$\omega = \begin{cases} \tau_3 & if\ r_1 < r_2 \\ \tau_4 & if\ r_2 < r_3 \\ \tau_5 & if\ r_1 < r_3 \end{cases} \quad (11)$$

where r_2, r_3, and τ_3 are random numbers between 0 and 1; τ_4 and τ_5 are random numbers generated according to the normal distribution and levy flight, respectively.

The nutcrackers that find pine seeds search for suitable locations to store them. This behavior corresponds to the first exploitation phase of the NOA algorithm and is expressed as follows:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^{t} + \omega \cdot \left(X_{bst,j}^{t} - X_{i,j}^{t}\right) \cdot |\lambda| \\ \quad +r_1 \cdot \left(X_{A,j}^{t} - X_{B,j}^{t}\right), & if\ \tau_1 < \tau_2 \\ X_{i,j}^{t} + \omega \cdot \left(X_{A,j}^{t} - X_{B,j}^{t}\right), & if\ \tau_1 < \tau_3 \\ l \cdot X_{bst,j}^{t}, & otherwise \end{cases} \quad (12)$$

where $X_{bst,j}^{t}$ is the current best position in the nutcracker swarm; λ is a random number generated using levy flight nutcracker positions; and l is a coefficient decreased linearly from 1 to 0 over iterations.

The transition between the exploration phase 1 and the exploitation phase 2 of the NOA algorithm is achieved as follows:

$$X_{i}^{t+1} = \begin{cases} \text{Eq. (10)} & if\ \xi_1 < P_{a1} \\ \text{Eq. (12)} & otherwise \end{cases} \quad (13)$$

where ξ_1 is a random number ranging between 0 and 1 and P_{a1} decreases linearly from 1 to 0 over iterations.

The food-searching and storing behavior of the nutcracker birds during the summer and fall periods correspond to the exploration phase 1 and exploitation phase 1, as described previously. On the other hand, during the winter and spring months, the birds focus on retrieving the stored food to ensure the survival of themselves and their young. In this context, the behavior of the nutcrackers in finding their stored food, which corresponds to the exploration phase 2, and the actions they take based on whether food is present in the storage locations correspond to the exploitation phase 2.

The nutcrackers, with their special abilities, are capable of remembering multiple reference points that help them find their stored locations. In the NOA algorithm, the number of reference points is selected as 2. Based on these reference points, the nutcrackers' behavior of finding the places where they stored food corresponds to the exploration phase 2, and it is modeled as follows:

$$X_{i}^{t+1} = \begin{cases} X_{i}^{t}, & if\ fitness(X_{i}^{t}) < fitness(R_{i1}^{t}) \\ R_{i1}^{t}, & otherwise \end{cases} \quad (14)$$

$$X_{i}^{t+1} = \begin{cases} X_{i}^{t}, & if\ fitness(X_{i}^{t}) < fitness(R_{i2}^{t}) \\ R_{i2}^{t}, & otherwise \end{cases} \quad (15)$$

where

$$R_{i1,j}^{t} = \begin{cases} X_{i,j}^{t} + \phi \cdot \cos(\theta) \cdot (X_{A,j}^{t} - X_{B,j}^{t}) + \phi \cdot RP, & if\ \theta = \pi/2 \\ X_{i,j}^{t} + \phi \cdot \cos(\theta) \cdot (X_{A,j}^{t} - X_{B,j}^{t}), & otherwise \end{cases} \quad (16)$$

$$R_{i2,j}^{t} = \begin{cases} X_{i,j}^{t} + \left(\phi \cdot \cos(\theta) \cdot \left((U_j - L_j) \cdot \tau_3 + L_j\right) + \phi \cdot RP\right) \cdot U_{2,j}, & if\ \theta = \pi/2 \\ X_{i,j}^{t} + \phi \cdot \cos(\theta) \cdot \left((U_j - L_j) \cdot \tau_3 + L_j\right) \cdot U_{2,j}, & otherwise \end{cases} \quad (17)$$

$$\phi = \begin{cases} \left(1 - \frac{t}{it_{max}}\right)^{\frac{2t}{it_{max}}} & if\ r_1 > r_2 \\ \left(\frac{t}{it_{max}}\right)^{\frac{2}{t}} & otherwise \end{cases} \quad (18)$$

where $R_{i1,j}^{t}$ and $R_{i2,j}^{t}$ are the reference positions in the memory of ith nutcracker; RP represents a random position vector; and θ is a random in the range between 0 and π.

According to the NOA algorithm, nutcracker birds exhibit food-searching behavior based on either the 1st or 2nd reference points (i.e. $R_{i1,j}^{t}$ and $R_{i2,j}^{t}$). However, when the nutcrackers reach their storage locations, they may encounter situations where the food is either present or absent. Due to various natural factors such as snow and rain, the food may not be there or may have been damaged. In such cases, to continue their survival, the nutcrackers will search for other promising areas. This behavior corresponds to the exploitation phase 2 of the NOA algorithm and is expressed as follows:

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^{t}, & if\ \tau_3 < \tau_4 \\ X_{i,j}^{t} + r_1 \cdot (X_{bst,j}^{t} - X_{i,j}^{t}) + r_2 \cdot (R_{i1,j}^{t} - X_{C,j}^{t}), & otherwise \end{cases} \quad (19)$$

$$X_{i,j}^{t+1} = \begin{cases} X_{i,j}^{t}, & if\ \tau_5 < \tau_6 \\ X_{i,j}^{t} + r_1 \cdot (X_{bst,j}^{t} - X_{i,j}^{t}) + r_2 \cdot (R_{i2,j}^{t} - X_{C,j}^{t}), & otherwise \end{cases} \quad (20)$$

where r_1, r_2, τ_3, τ_4, τ_5, and τ_6 are random numbers between 0 and 1 and $X_{C,j}^{t}$ is the position of the Cth nutcracker.

The transition between the 2nd Exploration phase and the 2nd Exploitation phase of the NOA algorithm is achieved as follows:

$$X_{i}^{t+1} = \begin{cases} \text{Eq. (13) and Eq. (14)}, & if\ \xi_2 < P_{a2} \\ \text{Eq. (18) and Eq. (19)}, & otherwise \end{cases} \quad (21)$$

where ξ_2 is a random number ranging between 0 and 1 and P_{a2} equals to 0.2.

4. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

The proposed method in this study is tested on two well-known test systems: the IEEE 9-bus and IEEE 15-bus test systems. Furthermore, the study is conducted under three scenarios, as outlined below:

• Scenario 1: The use of the standard relay characteristic function and its associated normal inverse characteristic (α =0.14 and β=0.02 in Eq. (1))

• Scenario 2: The use of the standard relay characteristic function and its associated extremely inverse characteristic (α =80 and β=2 in Eq. (1))

• Scenario 3: The use of the proposed exponential-based relay characteristic function

In Scenario 1 and Scenario 2, the relay operating times are calculated based on the traditional relay characteristic function, and the optimization process is performed. Scenario 1 employs the normal inverse characteristic type, which is commonly used in most studies in the literature, while Scenario 2 employs the extremely inverse characteristic type, which has been shown to provide better results than other standard characteristics in the literature [10]. Scenario 3 represents the usage of the proposed exponential-based relay characteristic function.

All optimization results are obtained using the Nutcracker Optimization Algorithm (NOA), with the algorithm control parameters chosen as in the original work [17]. The maximum number of iterations and the population size are set to 5000 and 50, respectively. To compare the performance of the NOA algorithm, the sand cat swarm optimization (SCSO) [20] and chameleon swarm algorithm (CSA) [21] are studied in this paper. The metaheuristic algorithms are based on randomness, which may cause variations in the results for each run [22]. Therefore, considering the potential changes due to randomness, each algorithm is run 20 times, and the best result is determined from these 20 runs.

Table 1. The bounds of problem constraints (Problem Kısıtlarının Sınırları)

System	Standard parameters				Proposed characteristic-based parameters		
	$\mathbf{TDS}_i$	$\mathbf{PS}_i$	$\boldsymbol{T_i}$	$\mathbf{CTI_{min}}$(s)	$\boldsymbol{\rho_i}$	$\boldsymbol{\gamma_i}$	$\boldsymbol{\mu_i}$
9-bus	0.025-1.2	taken from [2]	0.1-2	0.2	1-50	0.1-0.5	1-4
15-bus	0.1-1.1	0.5-2.5	0.1-1.1	0.2	1-50	0.1-0.5	1-4

The problem constraints are given in Table 1 for the test systems considered in this paper. Here, the problem constraints are selected with the same as in the references [16] and [23], for the IEEE 9-bus and IEEE 15-bus test systems, respectively. The aim is to make a fair comparison of the NOA algorithm with the literature methods including improved moth-flame optimization (IMFO) [16] and oppositional Jaya (OJaya) [23] algorithms.

4.1. Test System 1: IEEE 9-Bus System (Test Sistemi 1: IEEE 9-Bara Sistemi)

The single-line diagram of the IEEE 9-bus system is shown in Figure 2. The system includes a total of 24 directional overcurrent protection relays and 32 primary/backup relay pairs. The current transformer ratio associated with the relays is 500/1. Detailed information regarding fault currents and pickup setting limits related to the system can be found in reference [2].

Table 2 presents the optimal relay setting parameters obtained using the NOA algorithm for all considered scenarios. According to the results, lower relay operating times are achieved when using both the normal inverse and the proposed relay characteristic. However, when the extremely inverse characteristic is used, a significantly high OF value is observed. This is because, at high fault currents, the extremely inverse characteristic provides shorter relay operating times compared to the normal inverse characteristic. However, as seen in Table 1, a minimum relay operating time of 0.1 s is considered in the evaluations. Consequently, with this relay characteristic, it is not possible to avoid the penalty value given in Eq. (7) for relays R17, R19, R21, and R23, which are subjected to high fault current levels. On the other hand, using the proposed relay characteristic results in a 15% reduction in the OF value compared to the NI curve. The operating times of relay pairs are plotted in Figure 3.

Table 3 gives statistical optimization results for comparison in terms of minimum (Min), maximum (Max), average (Avg), and standard deviation (Std) of OF values over 20 independent runs. According to the results, the NOA algorithm is the best in terms of Min, Max, and Avg for all scenarios. For only Scenario 1, the Std value of the NOA algorithm is relatively higher than those of the others. However, considering the results in other metrics such as the Min value, the NOA algorithm provides a 42% reduction compared to the second-best result obtained via SCSO.

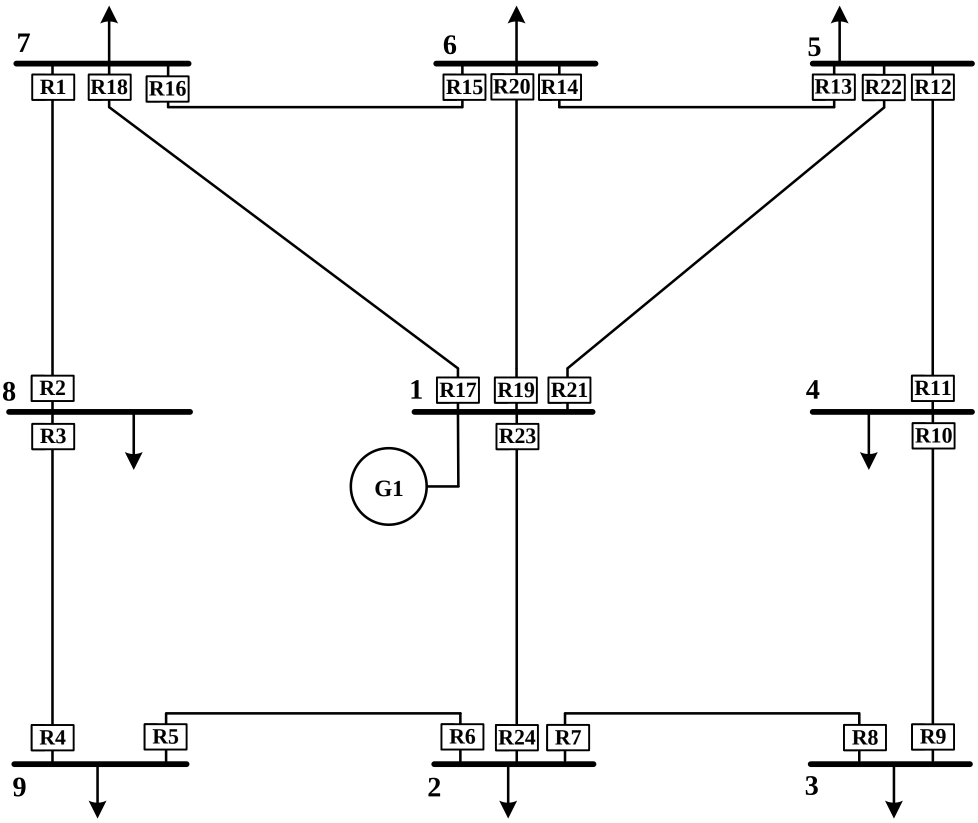


Figure 2. Single-line diagram of the IEEE 9-bus test system (IEEE 9-bara test sistemi tek hat şeması)

Table 2. Optimal relay settings obtained using the NOA for the IEEE 9-bus system (IEEE 9-bara sistem için NOA kullanılarak elde edilen optimal röle ayarları)

Relay	Scenario 1		Scenario 2		Scenario 3				
	TDS_i	PS_i	TDS_i	PS_i	TDS_i	PS_i	ρ_i	γ_i	μ_i
R1	0.0268	1.552	0.2890	0.639	0.4464	0.561	12.257	0.1696	1.600
R2	0.0250	0.761	0.0456	0.538	0.1549	0.703	6.768	0.1473	1.413
R3	0.0250	1.320	0.6409	0.248	0.4459	0.369	12.734	0.1533	1.558
R4	0.1556	0.076	0.2229	0.391	0.4715	0.412	8.763	0.1763	1.665
R5	0.0250	0.899	0.2282	0.263	0.2053	0.403	13.556	0.1831	1.715
R6	0.0260	1.634	0.3107	0.556	0.3527	0.585	13.037	0.1377	1.392
R7	0.0250	1.591	0.3243	0.543	0.2569	0.742	11.932	0.1340	1.334
R8	0.0250	0.899	0.4134	0.196	0.2613	0.377	16.899	0.1328	1.539
R9	0.0251	1.210	0.1712	0.445	0.4309	0.306	15.688	0.1472	1.539
R10	0.0251	1.318	0.1176	0.578	0.3034	0.448	17.556	0.1450	1.566
R11	0.0250	0.762	0.1160	0.339	0.2492	0.393	9.265	0.1806	1.648
R12	0.0251	1.032	0.3144	0.354	0.2269	0.496	12.912	0.1603	1.486
R13	0.0262	1.219	0.1800	0.612	0.3734	0.292	22.425	0.1566	1.524
R14	0.0257	1.425	0.5203	0.410	0.4066	0.427	15.651	0.1515	1.488
R15	0.0260	1.396	0.1765	0.702	0.2594	0.588	9.804	0.2309	1.807
R16	0.0250	1.341	0.5596	0.348	0.3856	0.353	11.598	0.2071	1.705
R17	0.0376	1.174	0.1125	1.104	0.1527	1.477	10.191	0.1596	1.379
R18	0.0250	1.103	0.0250	1.104	0.1566	1.416	7.208	0.1367	1.557
R19	0.0368	1.214	0.1264	1.027	0.1306	1.298	13.012	0.1490	1.322
R20	0.0250	1.027	0.0278	1.090	0.0611	1.317	6.936	0.1515	1.319
R21	0.0347	1.431	0.1125	1.103	0.1432	1.349	8.487	0.1515	1.300
R22	0.0250	1.103	0.0250	1.104	0.1833	1.323	6.869	0.1149	1.397
R23	0.0324	1.741	0.0879	1.266	0.2328	1.560	7.447	0.1354	1.271
R24	0.0250	1.266	0.0250	1.266	0.1083	1.461	8.190	0.1220	1.631
OF (s)	2.8322		213.6262		2.4046				

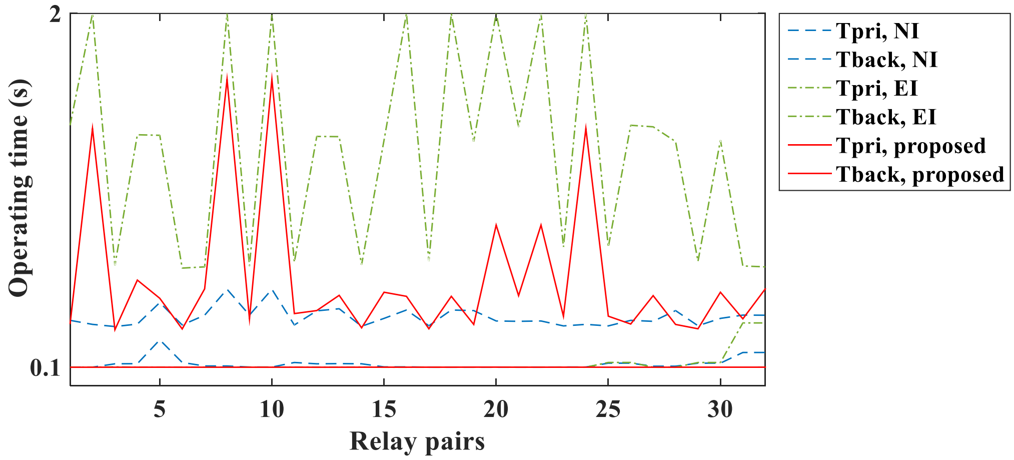


Figure 3. Operating times corresponding to the optimal relay settings obtained using the NOA for the IEEE 9-bus system (IEEE 9-baralı sistem için NOA kullanılarak elde edilen optimal röle ayarlarına karşılık gelen röle işlem süreleri)

Figure 4 shows the convergence curves obtained using different algorithms for the IEEE 9-bus test system. It is observed that the NOA algorithm exhibits a faster convergence performance compared to others for all scenarios. It can also be concluded that, by using the NOA algorithm, desired solutions can be achieved with a low number of iterations.

Table 3. Statistical optimization results over 20 runs for the IEEE 9-bus system (IEEE 9-baralı sistem için 20 çalıştırma üzerinden elde edilen istatistiksel optimizasyon sonuçları)

Scenario	Method	Min	Max	Avg	Std
Scenario 1	SCSO	4.863	6.334	5.467	0.638
	CSA	6.300	8.620	7.436	0.693
	NOA	2.832	5.258	4.087	0.710
Scenario 2	SCSO	629.559	1450.688	892.911	353.837
	CSA	218.329	1429.883	347.213	380.447
	NOA	213.626	213.659	213.641	0.012
Scenario 3	SCSO	4.920	1817.347	491.257	693.274
	CSA	3.583	1131.784	225.525	465.845
	NOA	2.405	2.475	2.422	0.025

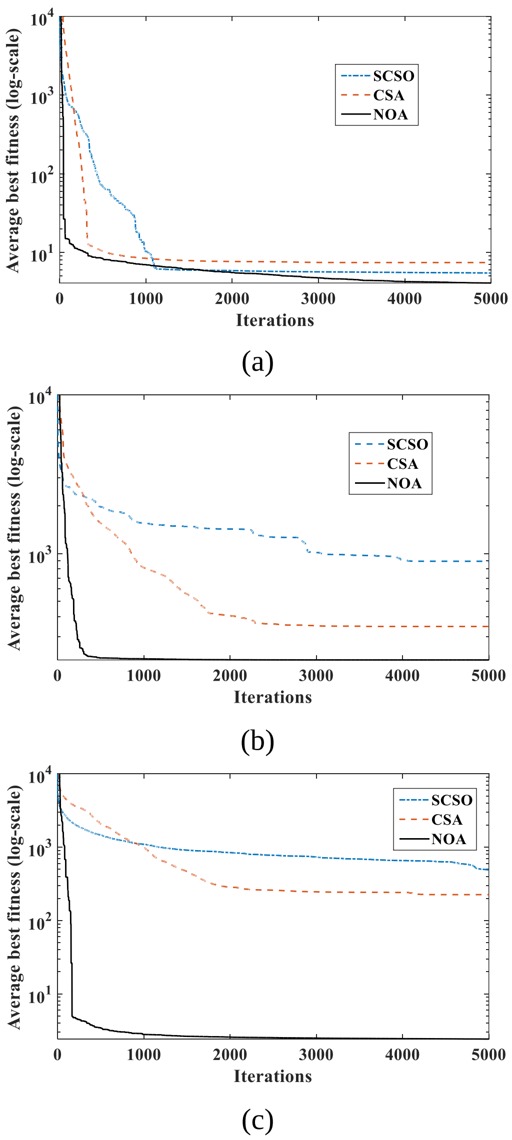


Figure 4. Convergence curves obtained for (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3 for the IEEE 9-bus system (IEEE 9-bara sistemi için (a) Senaryo 1, (b) Senaryo 2 ve (c) Senaryo 3'e ait yakınsama eğrileri)

According to the results given in Table 4, the NOA algorithm yields approximately a 5% reduction in OF value compared to the published result in [16].

Table 4. Comparison of the results for Scenario 1 for the IEEE 9-bus system (IEEE 9-baralı sistem için Senaryo 1'e ait sonuçların karşılaştırılması)

Method	IMFO [16]	SCSO	CSA	NOA
OF (s)	2.983	4.863	6.300	2.832

4.2. Test System 2: IEEE 15-Bus System (Test Sistemi 2: IEEE 15-Bara Sistemi)

The single-line diagram of the IEEE 15-bus distribution system is shown in Figure 5. The system includes a total of 42 directional overcurrent protection relays and 82 primary/backup relay pairs. Detailed data including the current transformer ratios and fault current can be found in [24].

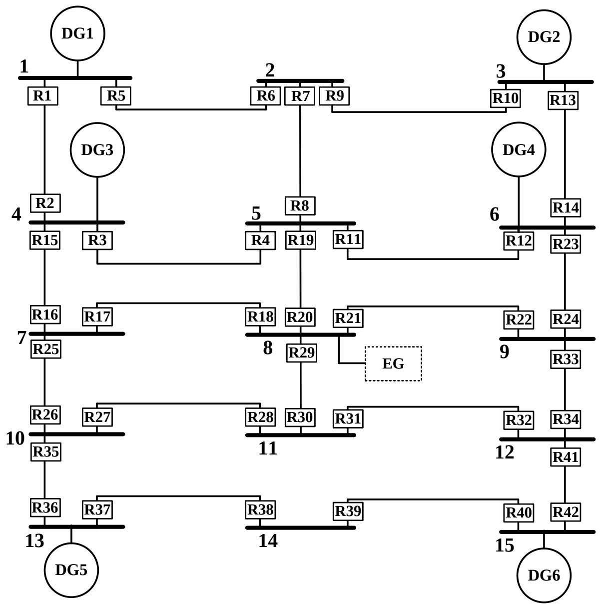


Figure 5. Single-line diagram of the IEEE 15-bus test system (IEEE 15-bara test sistemi tek hat şeması)

Similar to the 9-bus system, the proposed relay characteristic outperforms the standard relay characteristics. Especially, the proposed relay characteristic provides a 67% improvement in OF value compared to the NI curve. Furthermore, it can be seen that, by using the EI curve, it is not possible to avoid constraint violations, even in this system case.

Figure 6 gives the operating times of primary and backup relays for different scenarios for the IEEE 15-bus system. The constraint violations in minimum operating time for the scenario of the usage of the EI curve are clearly seen in the figure.

Table 5. Optimal relay settings obtained using the NOA for the IEEE 15-bus system (IEEE 15-bara sistem için NOA kullanılarak elde edilen optimal röle ayarları)

Relay	Scenario 1		Scenario 2		Scenario 3				
	TDS_i	PS_i	TDS_i	PS_i	TDS_i	PS_i	ρ_i	γ_i	μ_i
R1	0.1006	1.528	0.4564	0.912	0.3916	1.005	15.419	0.1774	1.578
R2	0.1009	1.308	0.4528	0.659	0.3985	0.747	12.481	0.2002	1.627
R3	0.1287	1.601	0.6897	1.087	0.4931	0.962	18.316	0.2051	1.884
R4	0.1021	1.506	0.4976	0.914	0.4547	1.047	15.068	0.2411	2.273
R5	0.1208	1.917	0.5641	1.086	0.3672	1.124	17.415	0.1776	1.524
R6	0.1242	1.610	0.5951	1.059	0.4986	1.104	16.889	0.1941	1.899
R7	0.1176	1.911	0.6999	0.914	0.4957	1.028	14.645	0.2395	2.176
R8	0.1099	1.531	0.5888	0.958	0.3964	0.661	16.496	0.2646	2.044
R9	0.1302	1.606	0.5930	1.130	0.3699	1.353	17.392	0.1864	1.762
R10	0.1154	1.614	0.6738	0.960	0.4701	1.028	14.616	0.1736	1.599
R11	0.1011	1.555	0.4065	1.006	0.3124	0.876	20.180	0.2092	1.846
R12	0.1007	1.583	0.4705	0.942	0.4478	0.961	13.679	0.2344	2.099
R13	0.1298	1.550	0.6463	0.943	0.3168	1.308	15.287	0.2359	1.802
R14	0.1007	1.436	0.4580	0.836	0.3619	0.848	21.915	0.1774	1.681
R15	0.1009	1.284	0.4274	0.713	0.4122	0.837	13.688	0.1719	1.519
R16	0.1007	1.766	0.4691	0.956	0.3748	1.226	17.951	0.1831	1.873
R17	0.1060	1.665	0.5206	1.160	0.2979	1.209	23.009	0.1804	1.717
R18	0.1005	1.352	0.4904	0.681	0.3901	0.878	10.646	0.2199	1.668
R19	0.1199	1.614	0.8057	1.011	0.4325	1.104	21.487	0.1769	1.757
R20	0.1034	1.373	0.4966	0.927	0.3561	1.145	16.273	0.2231	1.900
R21	0.1178	1.170	0.4235	0.735	0.2371	0.859	19.793	0.2167	1.678
R22	0.1136	1.614	0.6126	1.158	0.5553	1.098	12.519	0.1884	1.699
R23	0.1015	1.371	0.3885	0.754	0.3753	0.999	13.761	0.1870	1.617
R24	0.1015	1.609	0.6869	0.878	0.4738	1.019	12.809	0.1894	1.737
R25	0.1326	1.640	0.5586	0.907	0.3518	1.107	17.826	0.2323	2.142
R26	0.1132	1.736	0.5165	1.045	0.4780	0.878	16.458	0.2046	1.888
R27	0.1310	1.588	0.5900	0.913	0.4757	1.052	16.637	0.1808	1.885
R28	0.1572	1.613	0.4435	1.455	0.5408	0.984	14.872	0.2299	2.016
R29	0.1155	1.586	0.6078	0.850	0.3589	0.730	21.928	0.2276	1.824
R30	0.1159	1.591	0.5471	1.039	0.3855	1.073	13.977	0.2622	2.131
R31	0.1254	1.606	0.8645	0.844	0.3414	1.106	18.618	0.1978	1.747
R32	0.1190	1.597	0.4480	0.968	0.3378	0.951	22.356	0.1638	1.646
R33	0.1569	1.596	0.6982	0.846	0.4871	1.034	20.086	0.2023	2.200
R34	0.1511	1.448	0.5265	1.187	0.6237	1.278	11.904	0.1965	1.590
R35	0.1343	1.683	0.4557	1.021	0.4067	1.100	16.728	0.1657	1.718
R36	0.1159	1.798	0.4275	1.119	0.3269	1.030	25.795	0.2122	2.081
R37	0.1487	1.725	0.3988	1.295	0.5283	0.987	17.783	0.1969	1.996
R38	0.1455	1.646	0.4847	1.081	0.4402	1.045	22.216	0.2036	2.117
R39	0.1386	1.661	0.5113	1.003	0.3896	1.092	17.667	0.2211	1.571
R40	0.1537	1.630	0.6146	1.132	0.4026	1.087	21.585	0.1792	1.899

R41	0.1547	1.732	0.5134	1.216	0.4748	1.002	16.120	0.2439	2.091
R42	0.1119	1.544	0.6801	0.798	0.3377	1.015	17.688	0.1997	1.768
OF (s)	13.4769		1197.4265		4.5074				

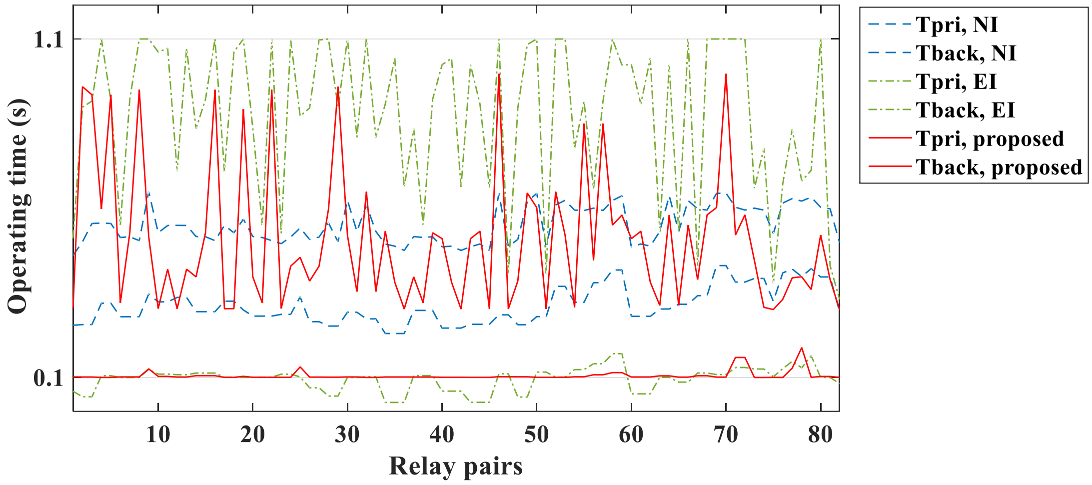


Figure 6. Operating times corresponding to the optimal relay settings obtained using the NOA for the IEEE 15-bus system (IEEE 15-baralı sistem için NOA kullanılarak elde edilen optimal röle ayarlarına karşılık gelen röle işlem süreleri)

Table 6. Statistical optimization results over 20 runs for the IEEE 15-bus system (IEEE 15-baralı sistem için 20 çalıştırma üzerinden elde edilen istatistiksel optimizasyon sonuçları)

Scenario	Method	Min	Max	Avg	Std
Scenario 1	**SCSO**	148.517	790.542	353.806	259.321
	CSA	19.277	20.958	20.273	0.740
	NOA	13.477	18.520	16.991	1.332
Scenario 2	**SCSO**	1325.657	1601.400	1428.593	114.117
	CSA	1260.094	1386.180	1325.172	47.223
	NOA	1197.427	1205.580	1199.427	3.201
Scenario 3	**SCSO**	2168.458	5540.362	3839.388	1320.427
	CSA	5.362	6.538	6.048	0.356
	NOA	4.507	4.738	4.571	0.078

The statistical results given in Table 6 confirm the effectiveness of the NOA algorithm for the optimal coordination of DOCRs. Similar to the 9-bus system, the NOA algorithm provides the best results in terms of Min, Max, and Avg for the 15-bus system as well. On the other hand, the CSA algorithm ranks second, performing better in minimizing relay operating times. Based on the results obtained for Scenario 3, it can be inferred that the SCSO algorithm struggles with problems that involve a high number of constraints. It gives significantly higher OF values compared to the CSA and NOA algorithms.

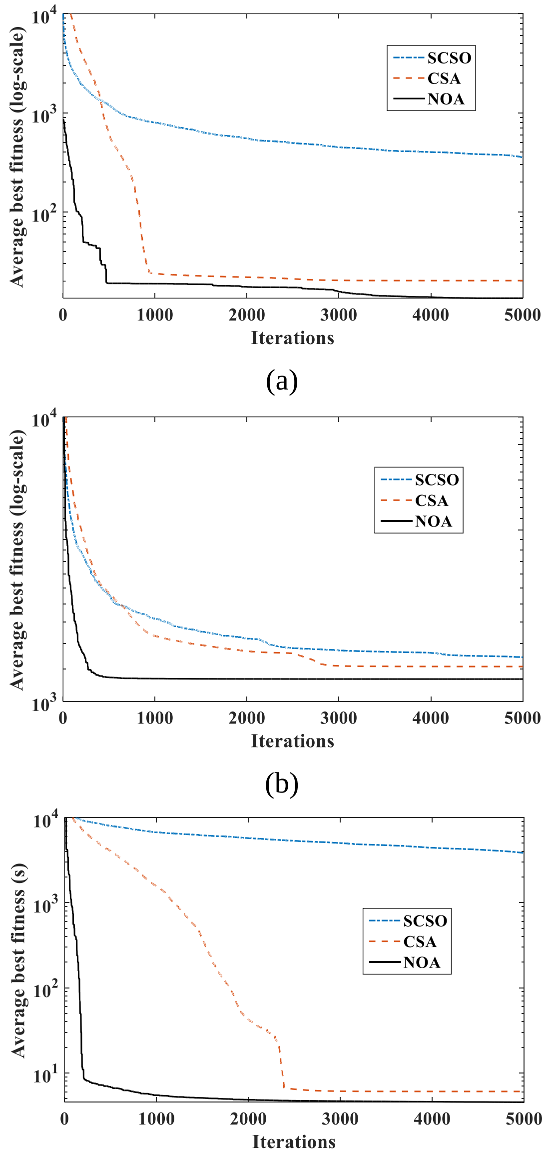
According to Figure 7, the NOA algorithm has a higher convergence performance compared to the others for the IEEE 15-bus system as well.

On the other hand, to compare the proposed exponential characteristic with the standard characteristics for a lower minimum operating time constraint, some additional experiments are also performed. In these experiments, the minimum operating time is set to 0.01 s. The results are given in Table 7. It is clearly seen that using the EI curve provides a significant reduction in the OF value compared to using the NI curve when the minimum operating time constraint is set to a lower value. However, the proposed characteristic with the NOA algorithm is still the best, even in these experiments.

The NOA algorithm improves the result published in the literature by 13.2% for the IEEE 15-bus system, as seen in Table 8.

Table 7. OF values considering a minimum operating time of 0.01 s for the IEEE 15-bus system (IEEE 15-bara sistem için minimum 0.01 s işletme süresi dikkate alınarak elde edilen OF değerleri)

Method	Scenario 1	Scenario 2	Scenario 3
SCSO	173.948	1.739	2188.256
CSA	18.947	1.797	3.751
NOA	13.552	1.408	0.811



(a) (b) (c)

Figure 7. Convergence curves obtained for (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3 for the IEEE 15-bus system (IEEE 15-bara sistemi için (a) Senaryo 1, (b) Senaryo 2 ve (c) Senaryo 3'e ait yakınsama eğrileri)

Table 8. Comparison of the results for Scenario 1 for the IEEE 15-bus system (IEEE 15-bara sistem için Senaryo 1'e ait sonuçların karşılaştırılması)

Method	OJaya [23]	SCSO	CSA	NOA
OF (s)	15.523	148.517	19.277	13.477

4.3. Discussion (Tartışma)

According to the results of the study, the proposed relay characteristic provides lower primary relay operating times compared to standard characteristics. On the other hand, the NOA algorithm, proposed for solving the problem, has demonstrated better performance than the other considered algorithms. In this regard, the use of the NOA algorithm, together with the proposed exponential-based characteristic, is to be highly effective in solving the optimal relay coordination problem.

As a drawback of the proposed approach, replacing standard characteristics with the proposed relay characteristic increases the number of decision variables from 2 to 5 for each relay. As observed for SCSO in this study, this situation may negatively impact the performance of the optimization algorithm. However, this disadvantage can be mitigated by using a well-established algorithm such as the NOA.

5. CONCLUSIONS (SONUÇLAR)

In this study, the use of an exponential-based relay characteristic for DOCRs and the nutcracker optimizer is proposed to solve the optimal coordination problem. The NOA algorithm, developed in recent years, offers advantages such as fewer control parameters and high convergence performance compared to other metaheuristic algorithms. On the other hand, the exponential-based relay characteristic is proposed to provide flexibility by overcoming the limitations imposed by conventional relay characteristics on relay operating times.

In the problem solution, both the exponential-based relay characteristic function and the conventional relay characteristic function based on the normal inverse and extremely inverse characteristics as specified in IEC standards are considered. The experiments are conducted under different scenarios to validate the effectiveness of the proposed exponential-based relay characteristic function. In addition, to evaluate the performance of the NOA algorithm, the SCSO and CSA algorithms are studied in the paper.

The results show that the use of the extremely inverse characteristic provides lower primary relay operating times compared to the use of the normal and extremely relay inverse characteristics. On the other hand, the NOA algorithm demonstrates consistent and reliable performance compared to the SCSO and CSA algorithms across all scenarios and test systems. When compared to results published in the literature, it is observed that the proposed exponential-based characteristic, combined with the NOA algorithm, provides highly effective results.

Considering all these findings, it can be concluded that the proposed method is a powerful alternative for solving the optimal coordination problem of DOCRs. In future work, the proposed method is planned to be applied to different objective functions and penalty values, as well as to distance-directional overcurrent protection coordination.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Alisan AYVAZ*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] Ayvaz A. A new and effective directional overcurrent relay coordination approach for IIDG-based distribution networks using different setting groups for peak and off-peak demand periods. Electric Power Systems Research. 2024; 237: 111017.

[2] Bouchekara HREH, Zellagui M, Abido MA. Optimal coordination of directional overcurrent relays using a modified electromagnetic field optimization algorithm. Applied Soft Computing. 2017; 54: 267-283.

[3] Abdelhamid M, Houssein EH, Mahdy MA, Selim A, Kamel S. An improved seagull optimization algorithm for optimal coordination of distance and directional over-current relays. Expert Systems with Applications. 2022; 200: 116931.

[4] Sarwagya K, Nayak PK, Ranjan S. Optimal coordination of directional overcurrent relays in complex distribution networks using sine cosine algorithm. Electric Power Systems Research. 2020; 187: 106435.

[5] Kamel S, Korashy A, Youssef AR, Jurado F. Development and application of an efficient optimizer for optimal coordination of directional overcurrent relays. Neural Computing and Applications. 2020; 32: 8561-8583.

[6] Alaee P, Amraee T. Optimal coordination of directional overcurrent relays in meshed active distribution network using imperialistic competition algorithm. Journal of modern power systems and clean energy. 2020; 9(2): 416-422.

[7] Korashy A, Kamel S, Houssein EH, Jurado F, Hashim FA. Development and application of evaporation rate water cycle algorithm for optimal coordination of directional overcurrent relays. Expert Systems with Applications. 2021; 185: 115538.

[8] ElSayed SK, Elattar EE. Hybrid Harris hawks optimization with sequential quadratic programming for optimal coordination of directional overcurrent relays incorporating distributed generation. Alexandria Engineering Journal. 2021; 60(2): 2421-2433.

[9] Ayvaz A. An enhanced sparrow search algorithm for model order reduction of proton exchange membrane fuel cell system. Transactions of the Institute of Measurement and Control. 2025; In press: 01423312241273838.

[10] Sorrentino E, Rodríguez JV. Effects of the curve type of overcurrent functions and the location of analyzed faults on the optimal coordination of directional overcurrent protections. Computers & Electrical Engineering. 2020; 88: 106864.

[11] Ramli SP, Mokhlis H, Wong WR, Muhammad MA, Mansor NN. Optimal coordination of directional overcurrent relay based on combination of Firefly Algorithm and

Linear Programming. Ain Shams Engineering Journal. 2022; 13(6); 101777.
[12] Ahmadi SA, Karami H, Sanjari MJ, Tarimoradi H, Gharehpetian GB. Application of hyper-spherical search algorithm for optimal coordination of overcurrent relays considering different relay characteristics. International Journal of Electrical Power & Energy Systems. 2016; 83: 443-449.
[13] Alasali F, Saidi AS, El-Naily N, Smadi MA, Holderbaum W. Hybrid tripping characteristic-based protection coordination scheme for photovoltaic power systems. Sustainability. 2023; 15(2): 1540.
[14] Hong L, Rizwan M, Rasool S, Gu Y. Optimal relay coordination with hybrid time–current–voltage characteristics for an active distribution network using alpha Harris hawks optimization. Engineering Proceedings. 2021; 12(1): 26.
[15] Yazdaninejadi A, Nazarpour D, Talavat V. Coordination of mixed distance and directional overcurrent relays: Miscoordination elimination by utilizing dual characteristics for DOCRs. International Transactions on Electrical Energy Systems. 2019; 29(3): e2762.
[16] Korashy A, Kamel S, Alquthami T, Jurado F. Optimal coordination of standard and non-standard direction overcurrent relays using an improved moth-flame optimization. IEEE Access. 2020; 8: 87378-87392.
[17] Abdel-Basset M, Mohame R, Jameel M, Abouhawwash M. Nutcracker optimizer: A novel nature-inspired metaheuristic algorithm for global optimization and engineering design problems. Knowledge-Based Systems. 2023; 262: 110248.
[18] Duan Z, Yu H, Zhang Q, Tian L. Parameter extraction of solar photovoltaic model based on nutcracker optimization algorithm. Applied Sciences. 2023; 13(11): 6710.
[19] Wu D, Yan R, Jin H, Cai F. An adaptive nutcracker optimization approach for distribution of fresh agricultural products with dynamic demands. Agriculture. 2023; 13(7): 1430.
[20] Seyyedabbasi A, Kiani F. Sand Cat swarm optimization: A nature-inspired algorithm to solve global optimization problems. Engineering with computers. 2023; 39(4): 2627-2651.
[21] Braik MS. Chameleon Swarm Algorithm: A bio-inspired optimizer for solving engineering design problems. Expert Systems with Applications. 2021; 174: 114685.
[22] Ayvaz A. An improved chicken swarm optimization algorithm for extracting the optimal parameters of proton exchange membrane fuel cells. International Journal of Energy Research. 2022; 46(11): 15081-15098.
[23] Yu J, Kim CH, Rhee SB. Oppositional Jaya algorithm with distance-adaptive coefficient in solving directional over current relays coordination problem. IEEE Access. 2019; 7: 150729-150742.
[24] Amraee T. Coordination of directional overcurrent relays using seeker algorithm. IEEE Transactions on Power Delivery. 2012; 27(3): 1415-1422.