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Comparative Analysis of Optimization Algorithms in Overcurrent Relay Optimization

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Saplings Growing up Algorithm, League Championship Algorithm, Genetic Algorithm, Whale Optimization Algorithm, Overcurrent Relay Coordination

Abstract: Optimization algorithms are commonly used to solve problems aiming to find the minimum or maximum value of a specific objective function. Optimization methods use both mathematical and heuristic approaches to select the best alternative. This study aims to minimize the Overcurrent Relay Coordination (ORC) problem of Overcurrent Relays using four optimization algorithms and compare the results. Overcurrent relays are critical protective devices that detect faults and minimize damage in power systems. Proper selection and adjustment of protective relays are essential to ensure the security of power systems. ORC consider numerous constraints such as relay operation times and settings, load changes, and maintenance requirements in an electric distribution system. The results generated by the Saplings Growing up Algorithm (SGA), League Championship Algorithm (LCA), Genetic Algorithm (GA), and Whale Optimization Algorithm (WOA) for the ORC problem in Hasançelebi transformer substation are compared. According to the results obtained, it is observed that the WOA produces faster results than other optimization algorithms.

Aşırı Akım Röle Optimizasyonunda Optimizasyon Algoritmalarının Karşılaştırmalı Analizi

Anahtar Kelimeler
Fidan Gelişim Algoritması, Lig Şampiyonluk Algoritması, Genetik Algoritma, Balina Optimizasyon Algoritması, Aşırı – Akım Röle Koordinasyonu

Öz: Optimizasyon algoritmaları, belirli bir amaç fonksiyonunun minimum veya maksimum değerini bulmayı amaçlayan problemleri çözmede yaygın olarak kullanılmaktadır. Optimizasyon yöntemleri, en iyi alternatifi seçmek için hem matematiksel hem de sezgisel yaklaşımları kullanmaktadır. Bu çalışmada Aşırı Akım Rölelerinin Koordinasyon (Overcurrent Relay Coordination - ORC) problemini dört optimizasyon algoritması kullanarak en aza indirgemeyi ve sonuçlarını karşılaştırmayı amaçlamaktadır. Aşırı akım röleleri, güç sistemlerinde arızaları tespit eden ve hasarı en aza indiren kritik koruyucu cihazlardır. Güç sistemlerinin güvenliğini sağlamak için koruma rölelerinin doğru seçimi ve ayarlanması önem arz etmektedir. ORC, bir elektrik dağıtım sisteminde röle çalışma süreleri ve ayarları, yük değişiklikleri ve bakım gereksinimleri gibi çok sayıda kısıtlamanın dikkate alınmasını içermektedir. Hasançelebi trafo merkezinin ORC sorunu için Fidan Gelişim Algoritması (Saplings Growing up Algorithm -SGA), Lig Şampiyonluk Algoritması (League Championship Algorithm - LCA), Genetik Algoritma (Genetic Algorithm - GA) ve Balina Optimizasyon Algoritması (Whale Optimization Algorithm - WOA) ile üretilen sonuçlar karşılaştırılmaktadır. Elde edilen sonuçlara göre, WOA'nın diğer optimizasyon algoritmalarına göre daha hızlı sonuçlar ürettiği görülmektedir.

1. INTRODUCTION

Many problems are frequently solved using optimization methods. In mathematics, optimization is the process of determining the minimum or maximum quantity of an equation. The goal of optimization theory and methods is to choose the optimum option given the objective function [1]. In addition to using mathematical approaches, heuristic techniques are also employed to solve optimization systems [2]. The words Meta and Heuristics are combined to generate the phrase Meta-

Heuristics in literature. It is described as a collection of techniques for solving issues using predetermined guidelines and processes [3]. This study intends to reduce the ORC problem utilizing two optimization methods and compare the outcomes with two previously investigated algorithms.

The structure of power systems has become increasingly complex with today's technological developments [4]. During the operation of power systems, protective relays are of great importance [5]. The principal purpose of protective relays is to quickly identify errors that may occur in electrical systems and to reduce or eliminate the damage caused by these faults. In this way, the damages that may occur during the operation of power systems can be prevented and the safety of electrical systems can be ensured. Protective relays include types such as distance protection, overcurrent, and differential relays. Ensuring the continuity and protection of energy in power systems is also an important issue in the field of engineering. Therefore, the correct selection and adjustment of protective relays are crucial for the protection of power systems [6]. The structures of power systems can encounter both permanent and temporary faults. These faults can negatively affect the operation of network equipment and even cause high-amplitude currents to damage network equipment. Therefore, taking safety measures in the structure of power systems is important [7]. One of the most common protective relays is the overcurrent relay [8].

Overcurrent relays are the primary protection devices of electrical distribution systems and prevent malfunction of power systems. These relays work in case of malfunction and take preventive measures to prevent damage to the system. In the past, communication between overcurrent relays was done with traditional methods, but later computerized methods were used [9, 10]. Traditional methods require manual processes such as determining the operating times and order of operation of relays, while computerized methods enable these processes to be carried out in a computer environment. Thanks to these methods, ORC can be performed more effectively and quickly [9, 11].

ORC requires consideration of numerous constraints in an electricity distribution system [12]. These constraints can include factors such as relay operating times, operating sequences, and operating frequencies. Therefore, in order to be properly implemented, ORC has to be formulated as an optimization problem that considers a number of constraints. This optimization problem aims to determine the operating times and sequences of relays and to find the optimal solution. This enables ORC to be conducted more efficiently and ensures system safety. Various optimization techniques are recommended for optimal coordination [13, 14]. Metaheuristic algorithms are algorithms that solve optimization problems by combining different methods. These algorithms are generally used to increase the solution time and/or solution quality of classical optimization algorithms. Additionally, metaheuristic algorithms have been used for ORC issues, with successful results in terms of both solution speed and quality. For example, metaheuristic algorithms such as Continuous Genetic Algorithm (CGA) [15] and Chaotic Firefly Algorithm (CFA) [16] provide effective results in ORC problems [12].

Razavi et al. [17], used GA for ORC. The presented objective function (OF) can solve coordination problems as well as problems with continuous or discrete time-setting multipliers (TSM) or time-dial settings (TDS). Two distinct power system network configurations were used to test the study. The outcomes attained show that this new approach is a flexible and successful method.

Alam et al. [18] examined the performance of five different meta-heuristic algorithms, including GA, Particle Swarm Optimization (PSO), Differential Evolution (DE), Harmony Search (HS), and Seeker Optimization Algorithm (SOA) for solving the protection coordination problem of oriented overcurrent relays. According to the study, among the five algorithms looked at, the DE algorithm fared the best.

Gaikwad et al. [19] used a tournament championship strategy in their study on the CloudSim simulator to enhance business planning for cloud architecture. Reducing time to market and offering cloud services at reasonable prices are the major objectives. The most effective strategy, according to the data, is ILCA.

Langazane et al. [20] study the effects of particle swarm optimization and genetic algorithms on overcurrent relay sensitivity and speed. The study has shown that evolutionary algorithm control parameters affect relay performance. Experimental results show that PSO converges faster than GA.

According to Rizal et al.'s [21] research utilizing genetic algorithms, the approach of choosing overcurrent relay settings with MATHCAD is still not ideal since it needs certain changes. Compared to conventional optimization strategies, this research appeared to offer an improvement in Overcurrent Relay coordination optimization.

Wadood et al. [22] evaluated the problem of optimally coordinating Directional Overcurrent Relays (DOCR) using the WOA algorithm. It has been put into use in six different systems to assess how well the suggested WOA is working. The six problematic models appear to be successfully minimized in simulation results of the WOA method. The results attested to the effectiveness and dependability of the suggested WOA as a tool for directional overcurrent relay coordination. Additionally, it is determined that the WOA findings outperform numerous well-known and up-to-date methods mentioned in the literature.

For optimal coordination of overcurrent relays in distribution systems, the GA approach was utilized in the work of Bedekar et al. [23]. But, a new target function was used to convert the constrained optimization problem into an unconstrained one using a penalty method, and during the mapping of binary variables to decimal values, TMS limits were used as variable limits due to relay operating time limits. In both examples, a minimum operating time of 0.2 s was assumed for each relay. The CTI value was taken as 0.57 s for Illustration I and 0.6 s for Illustration II. This shows that constraints can be created based on relay and breaker characteristics and system requirements, and the best coordination can be achieved. The algorithm has been tried on numerous systems and has consistently produced positive outcomes [23].

In their study, Khurshaid et al. [24], proposed hybrid metaheuristic algorithms based on WOA. The outcomes show that the suggested HWOA is a useful and trustworthy technique for directed ORC. The results obtained using HWOA suggest that it is better than WOA and many algorithms mentioned in the literature.

Seyyarer et al. [25], used SGA and LCA for ideal coordination of overcurrent relays in their study. In the study, TEIAS (Turkish Electricity Transmission Corporation) focused on the results of the ORC, which is commonly used in power systems, based on the inverse time setting in phase-to-phase short circuit faults.

In this study, the ORC problem is calculated using GA and WOA. A comparison of the results of these two algorithms with the previous LCA [25, 26] and SGA [25] studies is discussed. The findings show that WOA produces faster results compared to other algorithms.

2. MATERIAL AND METHOD

2.1. Saplings Growing up Algorithm

SGA is a meta-heuristic optimization algorithm designed by inspiring the growth process of saplings. This method places the parameters necessary for solving the problem on the saplings and performs operations on these saplings. The operators in the algorithm are designed to mimic the growth process of seedlings. The sapling planting operator is used to ensure the formation of saplings with a regular distribution in the search space. The branching operator is used in local search operations, while the matching operator is used to provide global search operations. In addition, the Vaccinating operator is used to facilitate information exchange between similar saplings [25-27].

In this way, candidate solutions in SGA are initially distributed regularly in the search space. Later on, both local and global search operations are performed and information exchange is made among similar solutions [27].

Since all of the seedlings in the solution space may be compared to plants, they must all be dispersed equally around the garden (Fig. 1).. Unless it is a problem with several criteria, each seedling represents a potential solution. All seedlings are solutions in a circumstance with several conditions. In order for seedlings to develop more quickly, a farmer will want to put them evenly spaced apart (Fig. 1) [28].

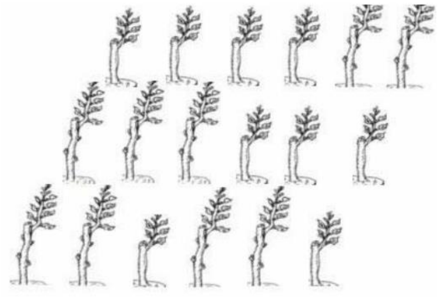


Figure 1. Evenly distributing saplings in the garden [28].

SGA can be implemented in two different ways; the pseudocode of the SGA-1 method is given in Algorithm 1, and the pseudocode of the SGA-2 method is given in Algorithm 2.

Algorithm 1: Pseudocode for SGA-1[27]

1.	$\boldsymbol{t}\leftarrow 0$ // Starting Time
2.	Saplings Planting $(\boldsymbol{P}(\boldsymbol{t}))$ // Initialization of Starting Population
3.	Fitness Evaluation $(\boldsymbol{P}(\boldsymbol{t}))$
4.	while Termination Criteria not met do
5.	$\boldsymbol{P1}(\boldsymbol{t}) \leftarrow$ Mating $(\boldsymbol{P}(\boldsymbol{t}))$
6.	$\boldsymbol{P2}(\boldsymbol{t})\leftarrow$ Branching $(\boldsymbol{P}(\boldsymbol{t}))$
7.	$\boldsymbol{P3}(\boldsymbol{t}) \leftarrow$ Vaccinating $(\boldsymbol{P}(\boldsymbol{t}))$
8.	Fitness Evaluation $(\boldsymbol{P1}(\boldsymbol{t}) \cup \boldsymbol{P2}(\boldsymbol{t}) \cup \boldsymbol{P3}(\boldsymbol{t}))$
9.	$\boldsymbol{P}(\boldsymbol{t}+\mathbf{1}) \leftarrow$ Selection $(\boldsymbol{P1}(\boldsymbol{t}) \cup \boldsymbol{P2}(\boldsymbol{t}) \cup \boldsymbol{P3}(\boldsymbol{t}))$
10.	$\boldsymbol{t} \leftarrow \boldsymbol{t}+\mathbf{1}$

Algorithm 2: Pseudocode for SGA-2 [27]

1.	$\boldsymbol{t} \leftarrow 0$ // Starting Time
2.	Sapling Planting $(\boldsymbol{P}(\boldsymbol{t}))$ // Setting up the initial population
3.	Calculate Fitness Values $(\boldsymbol{P}(\boldsymbol{t}))$
4.	while Termination Criteria not met do
5.	$\boldsymbol{P1}(\boldsymbol{t}) \leftarrow$ Mating $(\boldsymbol{P}(\boldsymbol{t}))$
6.	Calculate Fitness Values $(\boldsymbol{P1}(\boldsymbol{t}))$
7.	$\boldsymbol{Pm}(\boldsymbol{t})\leftarrow$ Selection $(\boldsymbol{P1}(\boldsymbol{t}) \cup \boldsymbol{P}(\boldsymbol{t}))$
8.	$\boldsymbol{P2}(\boldsymbol{t}) \leftarrow$ Branching $(\boldsymbol{Pm}(\boldsymbol{t}))$
9.	Calculate Fitness Values $(\boldsymbol{P2}(\boldsymbol{t}))$
10.	$\boldsymbol{Pb}(\boldsymbol{t}) \leftarrow$ Selection $(\boldsymbol{P2}(\boldsymbol{t}) \cup \boldsymbol{Pm}(\boldsymbol{t}))$
11.	$\boldsymbol{P3}(\boldsymbol{t}) \leftarrow$ Vaccinating $(\boldsymbol{Pb}(\boldsymbol{t}))$
12.	Calculate Fitness Values $(\boldsymbol{P3}(\boldsymbol{t}))$
13.	$\boldsymbol{P}(\boldsymbol{t}+\mathbf{1}) \leftarrow$ Selection $(\boldsymbol{P3}(\boldsymbol{t}) \cup \boldsymbol{Pb}(\boldsymbol{t}))$
14.	$\boldsymbol{t} \leftarrow \boldsymbol{t}+\mathbf{1}$

2.2. League Championship Algorithm

Firstly, it is necessary to look at the terms related to team sports for LCA proposed by Kashan. Sports leagues are competitions where a certain number of teams compete and are usually focused on team sports. The championship can be challenged by considering different criteria. Teams try to have the best record by competing with other teams in a certain number of matches. In order to judge if a scenario is a victory, a loss, or a tie, a rigorous win-loss-tie system or a scoring system with a set amount of points is employed. In some cases, bonus points can also be given to teams that meet certain criteria [25, 26, 29].

Similar to other algorithms inspired by nature, LCA evolves a population of solutions in the direction of an ideal solution. Each team (person) in the framework of a sports league symbolizes a viable answer to the issue that has to be resolved and is made up of n players, which corresponds to the number of variables. Team i plays against team j, which is related to its playing strength (fitness) according to an artificial weekly league program. The teams involved play against one another for $S \times (L - 1)$ weeks, where S is the number of seasons and week t is specified. This is used to determine the winning or losing team. Each team reviews the outcomes of the previous week's matches to prepare for the upcoming game and utilizes this data to create its new team. The expected efficient team formation is guided by the formation of a team with better playing strength than the current best team [29, 30].

LCA involves three main concepts:
• How the league schedule will be created.
• How winning or losing teams will be determined.
• How a new team will be created.

A schematic flowchart such as the one in Figure 2 can be used to illustrate the fundamental phases of the League championship algorithm [31].

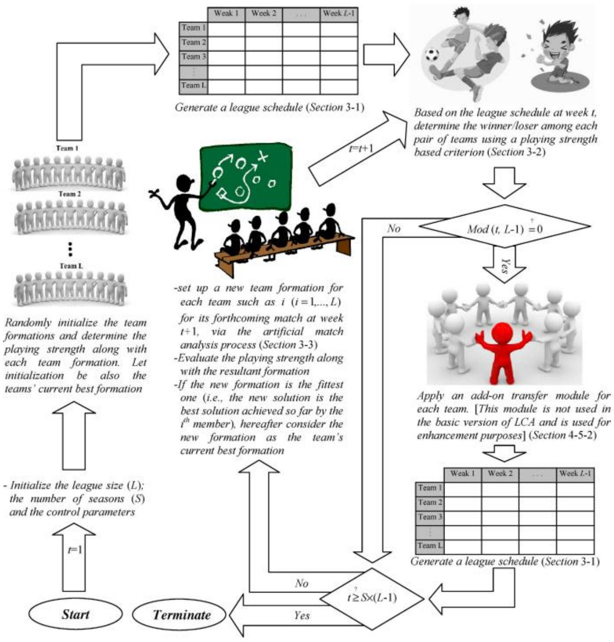


Figure 2. The league championship algorithm (LCA) flowchart [31].

Algorithm 3 provides the pseudocode for the LCA method.

Algorithm 3: Pseudocode for LCA [29]

1.	Set $t = 1$ and initialize the league size (L) and season count (S)
2.	Design a league schedule;
3.	Determine the playing strengths (function or fitness value) of each team by creating a population of L solutions. Permit each team's first formation to be the most effective one at the moment;
4.	While $t \le S.(L-1)$
5.	According to the league schedule for week t, determine the winner/loser among each pair of teams using a criteria based on game strength;
6.	$t = t + 1;$
7.	For $i = 1$ to L
8.	Using the team i's current best configuration and past occurrences, devise a new formation for the upcoming game. The resulting formation's playing strength should be evaluated;
9.	In the event that the new formation is superior (i.e., the outcome is the best outcome thus far for the i-th member of the population), accept the new formation as the team's current best configuration;
10.	End for
11.	If mod $(t, L-1) = 0$
12.	Design a new league schedule;
13.	End if
14.	End while

2.3. Genetic Algorithm

GA's are a class of computer models that were influenced by evolution. These algorithms employ recombination operators to basic data structures that resemble chromosomes to encode the probable solution of a particular issue and preserve crucial information. GA usually starts with a population of chromosomes that were produced at random [32]. After that, these structures are assessed, and opportunities for reproduction are given to chromosomes that represent better answers to the goal problem, giving them a greater opportunity to "breed" than those that represent inferior solutions. A solution's "goodness" is often determined in relation to the present population [32].

There are four main concepts in GA. These are:
• Initialization
• Selection
• Reproduction
• Termination

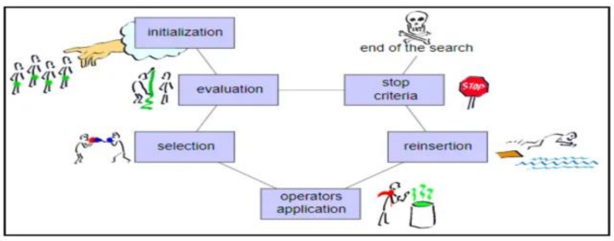


Figure 3. General scheme of GA [33].

Up till the termination condition is satisfied, this generational process is repeated [34]. Algorithm 4 contains the GA method's pseudocode.

Algorithm 4: Pseudocode for GA [34]

1.	Initialize $\boldsymbol{t = 1}$. Produce $\boldsymbol{N}$ solutions randomly to create the initial population $\boldsymbol{P1}$. Analyze the solutions in $\boldsymbol{P1}$'s fitness values.
2.	Crossover: Create a child population $\boldsymbol{Qt}$ by following the steps below:
3.	Based on the fitness values, choose two $\boldsymbol{Pt}$ solutions**,** $\boldsymbol{x}$ and $\boldsymbol{y}$**.**
4.	Create kids using the crossover operator, then include them in $\boldsymbol{Qt}$**.**
5.	Mutation: Apply mutation with a predetermined mutation rate to each $\boldsymbol{Qt}$ solution**.**
6.	Fitness assignment: Based on each solution's goal function value and fitness standing, assign a fitness value to it.
7.	Selection: Based on their fitness values, choose $\boldsymbol{N}$ solutions from $\boldsymbol{Qt}$**,** and copy them to $\boldsymbol{Pt + 1}$**.**
8.	Stop the search and return the current population if the termination requirement is satisfied. Otherwise, increment t by one and go to Step 2.

2.4. Whale Optimization Algorithm

Seyedali Mirjalili and Andrew Lewis first presented WOA in 2016, an algorithm based on humpback whales' fishing strategies [35]. Humpback whales usually feed on flocks of small fish near the water surface, and when they approach they form air bubbles to keep the fish together. This allows them to approach the fish unnoticed [36]. Figure 1 depicts the humpback whales' fishing strategies.

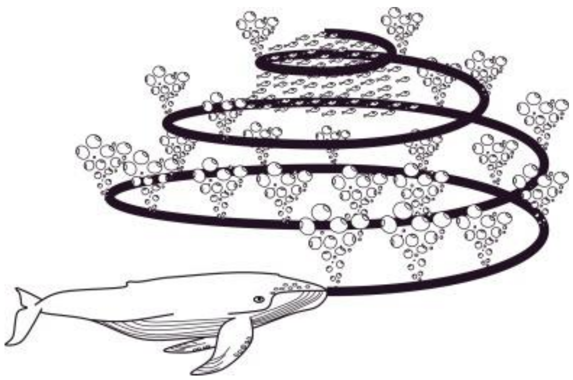


Figure 4. Hunting strategy of humpback whales [35].

In WOA, mathematical equations are created based on this hunting method. $\vec{A}$ and $\vec{C}$ are coefficient vectors, t is the current iteration, and X^* denotes the ideal solution vector. During each iteration, the value of a linearly decreases from 2 to 0, and r contains random vector variables between [0.1] [35].

There are three main concepts in WOA:
• Surrounding prey
• Bubble-net attack method (exploitation phase)
• Search for prey (exploration phase)

Algorithm 5 contains the WOA method's pseudocode.

Algorithm 5: Pseudocode of WOA [35]

1.	Determine the whales' starting population
2.	$\boldsymbol{Xi\ (i = 1, 2, \ldots\ldots, n)}$
3.	Determine each search agent's fitness.
4.	$\boldsymbol{X^*}$ = Best-known search agent.
5.	$\boldsymbol{t = 0}$
6.	while **(**$\boldsymbol{t <}$ maximum number of iterations**)**
7.	for: All search agents.
8.	Update $\boldsymbol{a, A, C, l,}$ and $\boldsymbol{p}$
9.	if $(\boldsymbol{p < 0.5})$
10.	if $(\lvert\boldsymbol{A}\rvert\ \boldsymbol{< 1})$
11.	else if $(\lvert\boldsymbol{A}\rvert\ \boldsymbol{>= 1})$
12.	Choose a search agent at random (Xrand)
13.	Adjust the chosen agent's position.
14.	end if
15.	else if $(\boldsymbol{p >= 0.5})$
16.	Update the position of the selected agent.
17.	end if
18.	end for
19.	Check if the selected agent goes outside the boundaries. If it does, give it the boundary values.
20.	Determine each search agent's fitness. Update $\boldsymbol{X^*}$ if a better solution is discovered.
21.	$\boldsymbol{t = t + 1}$
22.	end while
23.	return $\boldsymbol{X^*}$

2.5. Overcurrent Relay Coordination

Faults can occur in power systems due to various reasons, most of which are caused by the flow of current into the power system that exceeds the nominal level [30, 37]. One significant challenge that many power systems face is coordination problems. Either linear programming or nonlinear programming can be used to solve this issue. The pickup current settings in the linear coordination model are preset at values between the maximum load current and the minimum fault current, and optimization is accomplished by altering only the time dial. This model aims to prevent fault conditions that may occur in the power system, depending on the operating characteristics of the relays and system conditions. Depending on the properties of the relays, the nonlinear coordination model concurrently optimizes the time dial and pickup current settings. This model offers a more flexible approach and can more effectively prevent various fault conditions that may occur in the power system. However, the optimization of the nonlinear model can be more difficult and time-consuming [38].

Overcurrent relays operate in two types of modes, time-delayed and instantaneous. In our country, they are set to inverse time for phase-to-phase faults and to fixed time for phase-to-ground faults. These relays can provide protection in either forward or reverse direction depending on the power flow [6]. In this study, the settings of overcurrent relays used for the ORC in the TEIAS power system were investigated. In this system, coordination was based on inverse time settings to prevent phase-to-phase short-circuit (154 kV/OG 3-Phase Overcurrent) faults (Fig. 5). This coordination helps to prevent overcurrent faults that may occur in the system and reduce damage that may occur during system operation [26].

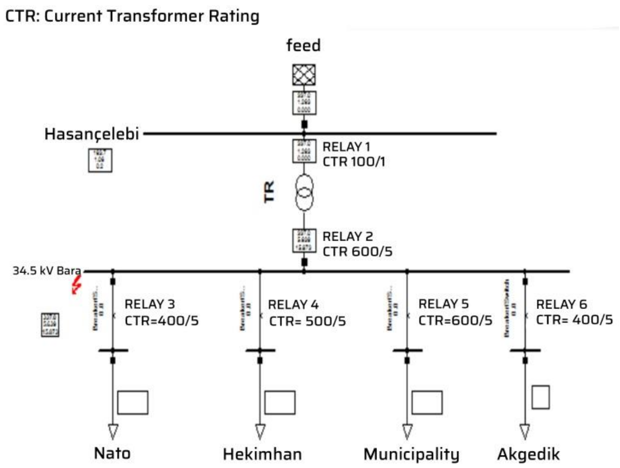


Figure 5. Example Transformer Substation Single Line update [25].

2.5.1. Formulation of overcurrent relay coordination problem

This study's primary goal is to reduce the operation times of overcurrent relays. To achieve this goal, an optimization is carried out assuming that all relays have the same characteristic features. The findings of this study show that overcurrent relay running periods may be significantly reduced, making a substantial contribution to electrical system safety [26].

The objective function in the ORC is expressed as equation 1.

$$Objective\ Function = min \sum_{i=1}^{n}(ti).m \qquad (1)$$

In this study, n represents the number of overcurrent relays in the power system, ti represents the operating time of each overcurrent relay, and m represents the probability of faults occurring in the power system. Considering phase-to-phase faults, the total minimum time of the relays is calculated based on the standard inverse-time characteristic. The characteristic equation used in this study is the standard inverse-time characteristic, expressed in equation 2 [26].

$$ti = \frac{0.14.\mathrm{td}}{(\frac{\mathrm{Ikd}}{\mathrm{Ip}})^{0.02}-1} \qquad (2)$$

The value of Ikd in Equation 2 is constant and represents the short-circuit current value. The pickup current of the relay is represented by the value of Ip. Relay operation time is represented by ti, while operating characteristic values are represented by td. The constraints used in optimization can be expressed within an estimated range based on the values used in the TEIAS system. These are:

The value of Ikd for relay 1 is 1263A, and for relays 2, 3, 4, 5, and 6, it is 5639A.

Constraint 1: $ti\_min \leq ti \leq ti\_max = 1s \leq ti \ \leq 2.2s$

The first constraint specifies the time order of the six relays as $t6, t5, t4, t3 \ \leq \ t2 \ \leq \ t1$. It states that the time of Relay 1, $t1$, should be greater than the time of Relay 2, $t2$. Additionally, the time of Relay 2, $t2$, should be greater than the times of the other relays. However, the times of Relays 3, 4, 5, and 6 are not ordered among themselves. Only these relay values should be less than $t2$ and $t1$. $t1$ should be 0.3 seconds greater than $t2$, and $t2$ should be 0.3 seconds greater than the times of the other relays.

Constraint 2: $tdmin \leq td \ \leq \ tdmax$ $(0.2 \ \leq \ td \ \leq \ 1)$

This constraint has been determined in accordance with the approach used by TEIAS in their system.

Constraint 3: This constraint concerns the starting times, therefore it includes Ip.

Relay 1	$117.152 \ \leq \ Ip \ \leq \ 128.65$
Relay 2	$523 \ \leq \ Ip \ \leq \ 575$
Relay 3	$400 \ \leq \ Ip \ \leq \ 420$
Relay 4	$500 \ \leq \ Ip \ \leq \ 510$
Relay 5	$600 \ \leq \ Ip \ \leq \ 610$
Relay 6	$400 \ \leq \ Ip \ \leq \ 420$

ti values will be calculated according to these constraints [26].

3. APPLICATIONS AND NUMERICAL RESULTS

Table 1 presents the results of SGA, LCA, GA, and WOA.

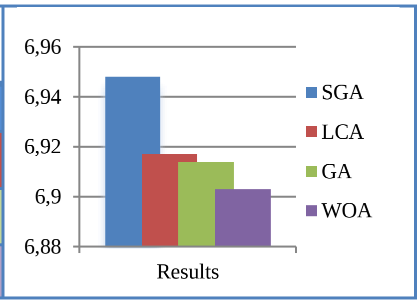
Table 1. Results of SGA, LCA, GA, and WOA

		Relay-1	Relay-2	Relay-3	Relay-4	Relay-5	Relay-6
T_i(s)	SGA	1.617	1.311	1.005	1.005	1.005	1.005
	LCA	1.605	1.305	1.001	1.001	1	1.005
	GA	1.606	1.305	1.002	1	1	1.001
	WOA	1.602	1.301	1	1	1	1

The results of SGA and LCA for the relay coordination problem of the Hasançelebi substation, as well as the results of GA and WOA, are presented in tables in this section. The minimum ti values obtained with SGA, LCA, GA and WOA are depicted in Table 2.

Table 2. Comparison of Results of Methods.

Method	Total T_i (s)
SGA	6.948
LCA	6.917
GA	6.914
WOA	6.903



The minimum ti values obtained from these four methods are shown graphically in Table 2. The results obtained are very close to the lower limits in the given constraints. The WOA method has, nevertheless, taken less time to compute than the other algorithms.

4. CONCLUSION

In this study, the performance of four distinct algorithms—SGA, LCA, GA, and WOA—for resolving the ORC issue was examined. Each algorithm was run 1000 times. SGA examines both global and local search steps and works with a small number of input parameters without using additional functions. The high success rate is mainly due to the fact that the initial population is not randomly selected. LCA, on the other hand, produces successful results by performing a high number of iterations in a short time. Traditional optimization methods can be limited in finding the global optimum point and sometimes get stuck at a local optimum point. Compared to conventional single-point search methods, GA claims to use a multi-point search strategy to locate the global optimal point. GA provides successful results in taking large search spaces and finding optimal combinations and solutions.

WOA provides faster results compared to other algorithms. When compared to other algorithms, WOA has a high search capacity and convergence speed, making it unique in its ability to use search agents to locate the best answer. The case studies in this paper are also analyzed using several optimization algorithms as demonstrated in the literature, and the suggested WOA algorithm produces a better optimum solution than the alternatives. Comparing the output values obtained by solving other problems using the four optimization algorithms included in this study is among the planned studies.

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