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Optimization Analysis of Protection Coordination in Loop Distribution Systems with Integrated Distributed Generation Using the Firefly Algorithm and Conventional Methods

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ABSTRACT: This study evaluates the comparison between conventional methods and the firefly method in the protection coordination of power systems with the addition of Distributed Generators (DG). DG is a crucial component in modern systems that can influence the performance of protection and existing protection coordination. Conventional methods involve relay setting adjustments and fault current coordination, but the addition of DG can significantly alter system characteristics, affecting the performance of conventional methods. This study introduces the firefly method, which utilizes an optimization algorithm inspired by the light-emitting behavior of fireflies to dynamically adjust relay settings, considering system changes due to the addition of DG. The results indicate that the firefly method enhances protection coordination performance by being more adaptive to system changes. The simulation results show that the operating time of relay 2 in Scheme 1 was reduced from 0.559 seconds (manual method) to 0.364 seconds (firefly method). The validation was conducted using the ETAP simulation platform. Thus, this study finding that implementing the firefly method in power system protection coordination with DG integration can improve system reliability and the overall efficiency of DG utilization. This method offers a more adaptive and responsive solution to changes in modern power systems.

Keyword: *Protection Coordination; Firefly Method; Conventional Method*

I. INTRODUCTION

The integration of Distributed Generators (DGs) has become increasingly common in contemporary power systems due to their ability to enhance supply reliability, support operational efficiency, and facilitate the use of renewable energy sources. Although DGs offer numerous advantages, their inclusion in the grid also presents new protection coordination challenges. The changes in power flow direction and fault current levels introduced by DGs can reduce the accuracy and selectivity of existing protection schemes, thereby requiring comprehensive adjustments to relay settings and coordination mechanisms [1]

Conventional protection coordination approaches typically involving static relay settings and predefined fault current thresholds are often insufficient to manage the dynamic behavior introduced by DGs [2]. These rigid methods can result in delayed fault isolation or miscoordination, which in turn may compromise system reliability and reduce operational performance [3].

While previous studies have applied various optimization techniques, such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and the Firefly Algorithm (FA), most have focused on radial distribution systems [4]. Research on loop configurations, which are more complex and sensitive to coordination issues, remains limited. In this regard, the Firefly Algorithm has shown promise due to its ability to adaptively optimize protection settings based on real-time system conditions, particularly those influenced by DG integration [5].

This study seeks to investigate the performance of the Firefly Algorithm compared to traditional methods in optimizing protection coordination within a loop distribution system that includes DGs. It focuses on evaluating how each approach accommodates dynamic changes caused by DGs and how effectively they maintain system reliability and efficiency. The findings are expected to offer critical insights for developing more adaptive and resilient protection strategies in modern power networks, especially as DG penetration continues to grow in the coming years.

II. THEORETICAL FRAMEWORK

In the field of power system protection coordination, numerous methods have been developed to enhance system reliability and operational efficiency. One of the primary challenges in this area is adapting protection schemes to dynamic changes resulting from the integration of Distributed Generators (DGs). This literature review is organized into several key sections as outlined below.

Distributed Generation (DG)

Distributed Generation (DG) refers to a decentralized approach to electricity generation, where energy sources are located close to consumers or integrated within existing power distribution networks. This system is designed to promote sustainability through the use of renewable energy sources, enhance supply reliability by minimizing the risk of central grid disruptions, improve efficiency by reducing transmission losses, and lower operational costs by utilizing local energy resources [6]. According to [7], DG has a considerable impact on power systems, including changes in voltage profiles and an increase in short-circuit levels. Key components of DG systems include renewable energy sources [8], generators, inverters, energy storage systems, and advanced control and monitoring technologies to optimize system performance. Furthermore, grid connection systems and smart grid technologies enable more efficient integration of DG into the main power network. As discussed in recent studies [9], these technologies present both challenges and opportunities in DG integration. The development and implementation of DG technologies are also supported by energy policies aimed at transforming power systems into more sustainable and adaptable infrastructures that meet future energy demands [10].

Power System Protection

Power system protection is a critical component in electrical networks, tasked with detecting and responding to faults promptly to maintain system stability and reliability. Protection design involves selecting appropriate components such as relay types, circuit breakers, fuses, current transformers, and ensuring proper coordination among protection devices to deliver optimal performance. One widely used protection device is the Overcurrent Relay (OCR), which functions by detecting fault currents and triggering the circuit breaker to prevent equipment damage. With the growing integration of Distributed Generation (DG) into distribution networks, traditional radial network configurations have evolved into multi-source systems. This transformation alters the fault current paths and magnitudes, potentially affecting the performance of pre-configured protection schemes. As a result, more adaptive protection strategies are required to accommodate these changes and ensure that protection coordination remains effective in DG-integrated power systems [11].

Short-Circuit Current Calculation

The three-phase short-circuit current can be calculated using a basic formula that considers the system's positive sequence reactance and nominal phase-to-neutral voltage:

$$Isc_{3\phi} = \frac{Vln}{X_1} \tag{2.1}$$

Where:

1. Vln is the nominal line-to-neutral voltage.
2. X_1 is the positive sequence reactance of the system.

This calculation is essential in power system analysis to determine the required capacity of protection equipment such as circuit breakers, ensuring they can interrupt fault currents effectively and prevent equipment damage [12]. A phase-to-phase short circuit occurs when two phase conductors come into contact without involving the ground. The fault current under this condition can be calculated using the following formula:

$$Isc_{2\phi} = \frac{V_{ll}}{X_1+X_2} \tag{2.2}$$

Where V_{ll} is the line-to-line voltage, and $X_1 + X_2$ are the positive and negative sequence reactances, respectively. If both phase impedances are equal $X_1 = X_2$, the equation can be simplified as:

$$Isc_{2\phi} = \frac{\sqrt{3}\ Vln}{X_1+X_2} \tag{2.3}$$

Furthermore, by applying mathematical identities, the two-phase short-circuit current can be expressed as:

$$Isc_{2\phi} = \frac{1}{2}\sqrt{3}\,\frac{Vln}{X_1} = 0{,}866 Isc_{3\phi} \tag{2.4}$$

This result indicates that the magnitude of the two-phase short-circuit current is approximately 86.6% of the three-phase short-circuit current.

Firefly Algorithm

The FA is a nature-inspired optimization method, which mimics the social flashing behavior of fireflies. In this algorithm, each potential solution is represented as a firefly that moves based on its attractiveness and a random exploratory component [12] [13]. A firefly with higher brightness corresponding to a better objective function value attracts others with lower brightness, guiding the search toward optimal solutions. The brightness of each firefly is inversely related to the distance between individuals, while the inclusion of randomness ensures broader exploration of the solution space. The algorithm’s movement and attraction mechanisms are governed by the following principles:

1. Fireflies are attracted to brighter individuals.
2. Less bright fireflies move toward those that are brighter.
3. Brightness is proportional to the quality of the objective function.

Mathematically, the attractiveness β\betaβ between two fireflies is modeled as:

$$\beta(r) = \beta_0 e^{-\gamma . r^n} \tag{2.5}$$

The position update rule for firefly is expressed as:

$$x_i = x_i + \beta(r) \times (x_i - x_j) + \alpha\left(\text{rand} - \frac{1}{2}\right) \tag{2.6}$$

In the context of overcurrent relay protection coordination, FA has been applied to optimize settings such as pickup current and time dial settings. The Coordination Time Interval (CTI), which is the minimum time margin between the operation of a primary and backup relay, typically ranges between 0.2–0.4 seconds to maintain selectivity.

The Inverse Time Dial Setting (TDS) coefficients vary based on the type of inverse curve used in overcurrent relays:

1. Standard Inverse : $\alpha = 0.02$, $k = 0.14$
2. Very Inverse : $\alpha = 1.00$, $k = 13.50$
3. Extremely Inverse : $\alpha = 2.00$, = $k = 80.00$

Compared to conventional optimization methods, the Firefly Algorithm demonstrates rapid convergence and strong performance in handling non-linear, multi-dimensional optimization problems [13]. Recent developments have also introduced the Chaotic Firefly Algorithm (CFA), which incorporates chaotic maps to enhance global search capability and avoid local optima [14]. The application of CFA in overcurrent relay coordination has shown significant improvements in optimization efficiency and solution quality [15][16].

III. METHODS

This study is designed to optimize protection coordination in power distribution systems by combining ETAP simulation with Firefly Algorithm (FA)-based optimization. The primary objective is to enhance the reliability of protection schemes by determining the optimal values of Time Dial Setting (TDS) and pickup current (Ipickup).

The methodological framework consists of several key stages: modeling the power system, manually calculating initial protection parameters, performing optimization using the Firefly Algorithm, and validating the results through ETAP simulations. The simulation phase includes fault scenario analyses to determine maximum fault currents, which serve as the foundation for protection coordination.

The research begins with the construction of a power system model in ETAP, followed by the extraction of fault current data and manual computation of TDS and Ipickup values. Subsequently, the Firefly Algorithm is applied to optimize these parameters, aiming to minimize coordination time intervals and ensure selectivity between primary and backup relays. The optimized settings are then re-evaluated within ETAP to verify that the protection coordination is effective and complies with standard protection requirements.

This study aims to implement protection coordination in power distribution systems using an optimization approach based on the Firefly Algorithm (FA), as illustrated in the flowchart in Figure 1. The research steps are described as follows:

1. Loop System Design Using ETAP
   A power system model is developed using ETAP software. Technical data, including network configuration, load characteristics, and protection parameters, are incorporated into the system. The model is constructed with consideration of both Distributed Generation (DG) and loop system configurations to enhance system reliability.
2. Fault and Load Current Data Collection
   Simulations are performed to obtain the maximum fault current (ISC) and full-load current (IFLA). These values serve as the basis for setting protection relays.
3. Manual Calculation of TDS and Ipickup
   Initial values of the Time Dial Setting (TDS) and pickup current (Ipickup) are manually calculated using conventional methods, based on IEC or IEEE standards. These calculations take into account overcurrent relay characteristics and coordination between primary and backup relays.
4. Optimization Using Firefly Algorithm (FA)
   The Firefly Algorithm is applied to optimize the TDS and Ipickup values to achieve effective protection coordination. The objective function is designed to minimize the operating time of the primary relay while maintaining selectivity with the backup relay. Key FA parameters—such as the number of fireflies, light absorption coefficient, and number of iterations—are determined based on initial experimentation.
5. Testing Optimized TDS and Ipickup in ETAP
   The optimized values obtained through FA are implemented into the ETAP system model. Protection coordination simulations are carried out to verify that the relays operate according to the desired selectivity criteria.
6. Result Analysis and Validation
   Simulation outcomes are compared with manual calculations to assess the effectiveness of the FA-based optimization. Validation focuses on whether the resulting protection coordination meets industry standards and improves overall system reliability.
7. Conclusion
   Conclusions are drawn based on the optimization and simulation results. Recommendations are provided regarding the practical application of the proposed method in modern power systems.

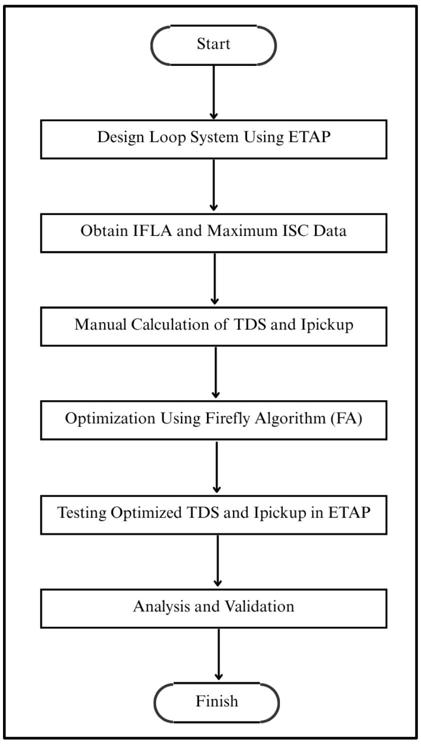


Figure 1. Research Steps

Protection Coordination Optimization Using Firefly Algorithm

Prior to the optimization process, the Firefly Algorithm (FA) is configured with the following parameters: number of fireflies = 50, number of iterations = 2500, $\alpha = 0.5$, $\beta = 0.2$, and $\gamma = 1.0$.

1. The **α** parameter acts as the randomization factor, controlling the level of exploration in the solution space.
2. **β** represents the attractiveness between fireflies; higher values encourage stronger attraction toward better solutions.
3. **γ** regulates the light absorption coefficient, which determines how rapidly attractiveness decays with distance, thereby influencing the search range.

These values fall within the general range that is effective for non-linear and multimodal optimization problems: $\alpha \in [0.2–0.5]$, $\beta \in [0.1–0.3]$, and $\gamma \in [0.5–1.0]$ [11], [12].

Optimization Steps Using Firefly Algorithm (FA) for Protection Coordination:

1. Data Collection
   Collect data from ETAP simulation, including full-load current (IFLA), maximum short-circuit current (ISC), current transformer (CT) ratios, and the pairing of primary and backup relays.
2. Objective Function Formulation
   Define an objective function that minimizes the total relay operating time while ensuring coordination between the primary and backup relays.
3. Parameter Initialization
   Initialize the TDS and pickup current (Ipickup) values randomly within predefined bounds.
   Constraints:
    1. $TDS_{min\leq}TDS \leq TDS_{max}$
    2. $1.05 \times IFLA \leq I_{P\leq}1.4 \times IFLA$
4. Light Intensity Calculation
   Compute light intensity based on the difference between actual TDS and the relay's operating time (top). The smaller the difference, the brighter the firefly.
5. Attractiveness Coefficient Calculation

Determine the attractiveness coefficient (β) using the exponential function of the distance between fireflies.

6. Firefly Movement
   Dimmer fireflies move toward brighter ones, representing better solutions in the search space.
7. Parameter Update
   Update the fireflies' positions, attractiveness, and randomization components to explore new candidate solutions.
8. Constraint Evaluation
   Ensure that the following coordination conditions are met:
    1. Coordination Time Interval (CTI) between primary and backup relays is between 0.2 – 0.4 seconds
    2. The operating time of the primary relay does not exceed 1 second
9. Determination of Best Parameters
   Assign Pbest (optimal TDS value) and Pnotbest (initial TDS value) based on the optimization results.
10. Optimization Result
    The iteration stops when the maximum iteration count is reached. The final output is the optimal TDS value for overcurrent protection coordination in the power system.

IV. DISCUSSION

This study aims to optimize protection coordination in a distribution system using the FA. The process begins with modeling the electrical power system in ETAP, which involves selecting equipment, configuring the network topology, and conducting short-circuit analysis to obtain Full Load Amperes (IFLA) and maximum Short-Circuit Current (Isc). These values serve as the basis for calculating the Time Dial Setting (TDS) and pickup current (Ip) for the protection relays.

Protection Coordination Using Manual Calculation

Manual protection coordination serves as a baseline reference to compare with the results obtained through Firefly Algorithm (FA) optimization. In this approach, relays are initially configured in **low-set mode**, and iterative calculations are performed until the TDS values of all relays converge. The coordination process is carried out in two directions: Clockwise (R1–R6) and Counterclockwise (R7–R12).

In the clockwise sequence, the calculation starts with R6 as the primary relay, which must coordinate with R5 as the backup relay, then R5 with R4, R4 with R3, and so on until R1 coordinates again with R6, completing the loop. If the TDS value of R6 changes significantly after the first iteration, all relay settings are recalculated and readjusted until stable coordination is achieved. For example, in the initial stage, R6 is assumed to have a TDS value of 0.03 (within the acceptable range of 0.025 to 1.2), while R5 acts as the backup relay. The iterative process continues until all relays in the system meet optimal coordination criteria.

1. Rele 6 (Main)

Curve *Type* : IEC *Very Inverse*
Isc : 1520 A
FLA : 354 A
CT ratio : 500/5

Low Set Current Setting

$I_{set} = 1{,}05 \times FLA = 372$

$Tap = \frac{I_{set}}{CT} = 3{,}72$

Time Opration

Dipilih TDS = 0,03

$$\text{TOP R6} = \frac{13{,}50 \text{ x TDS}}{\left[\left(\frac{\text{I}_{\text{Fault}}}{\text{Iset}}\right)^{1} - 1\right]}$$

$$= \frac{13{,}50 \text{ x } 0{,}03}{\left[\left(\frac{1520}{372}\right)^{1} - 1\right]}$$

$$= 0{,}2451\text{s}$$

2. **Rele 5 (*Backup*)**

Kurva *Type* : IEC *Very Inverse*
Isc : 1060 A
FLA : 227,8 A
CT ratio : 500/5

Low Set Current Setting

I_{set} = 1,05 x FLA = 239

Tap = $\frac{\text{I}_{\text{set}}}{\text{CT}}$ = 2,39

Time Opration

TOP R5 = TOP R6 + CTI = 0,2451 + 0,2 = 0,4451s

TOP R5 then used to calculate TDS R5

$$\text{TOP R5} = \frac{13{,}50 \text{ x TDS}}{\left[\left(\frac{\text{I}_{\text{Fault}}}{\text{Iset}}\right)^{1} - 1\right]}$$

$$0{,}4451 = \frac{13{,}50 \text{ x TDS}}{\left[\left(\frac{1060}{239}\right)^{1} - 1\right]}$$

$$= 0{,}122$$

After the first iteration, the R6 configuration is updated to coordinate with R1, closing the loop. If a significant change occurs in the R6 setting, the previous process is repeated, readjusting the settings of all relays in the loop. The results of the manual calculations are shown in Tables 1 and 2.

Protection Coordination Optimization Using Firefly Algorithm

The optimization process using the Firefly Algorithm (FA) was applied to four different generation scenarios in order to determine the most optimal Time Dial Setting (TDS) and pickup current (Ipickup) values, with the objective of minimizing the total relay operating time. The four generation schemes are described as follows:

1. **Scheme 1**: Main generator, DG2, and DG1 connected.
2. **Scheme 2**: Main generator and DG1 connected.
3. **Scheme 3**: Main generator and DG2 connected.
4. **Scheme 4**: Only the main generator connected.

The optimization process involved multiple simulation trials for each scheme to obtain the optimal values of TDS and Ipickup that result in the shortest total operating time while maintaining protection coordination requirements. Table 3 presents the fault current data for primary and backup relays, which are used in the optimization process using the Firefly Algorithm.

Table 1. Results of Manual Calculations in Scheme 1 and Scheme 2

Rele	TDS	Ipickup	TOP	Rele	TDS	TAP	TOP
1	0,85936	1,8186	0,67663	1	0,80573	1,8186	0,68256
2	0,64832	1,8207	0,58847	2	0,61692	1,8207	0,59281
3	0,47254	1,8186	0,49407	3	0,78483	1,0857	0,49339
4	0,19109	3,003	0,39938	4	0,1752	2,99565	0,37282
5	0,16153	2,3919	0,32381	5	0,07304	2,99565	0,25022
6	0,06533	3,717	0,28547	6	0,12034	1,8186	0,28189
7	0,38339	3,717	0,65032	7	0,29694	4,48245	0,64595
8	0,4819	2,3919	0,58924	8	0,36144	2,99565	0,57538
9	0,27134	3,003	0,5141	9	0,20736	2,99565	0,47099
10	0,37765	1,8186	0,4711	10	0,52972	1,0857	0,44078
11	0,28234	1,8207	0,41115	11	0,22375	1,8207	0,37465
12	0,22497	1,8186	0,39788	12	0,18504	1,8186	0,3699
13	0,17649	4,73813	0,7106	13	0,18178	4,73813	0,963

Table 2. Results of Manual Calculations in Scheme 3 and Scheme 4

Rele	TDS	Ipickup	TOP	Rele	TDS	TAP	TOP
1	1	0,83637	1,8186	0,68035	1	0,80078	1,8186
2	2	0,62452	1,82175	0,57572	2	0,59405	1,8228
3	3	0,34874	1,82175	0,4426	3	0,31623	1,8228
4	4	0,10143	3,92595	0,35427	4	0,08006	3,9249
5	5	0,10142	2,9988	0,31581	5	0,02158	3,9249
6	6	0,16877	1,8186	0,35777	6	0,07826	1,8186
7	7	0,27201	4,48665	0,62853	7	0,21291	5,4411
8	8	0,33475	2,9988	0,56464	8	0,24208	3,9249
9	9	0,17596	3,92595	0,48136	9	0,13192	3,9249
10	10	0,32612	1,82175	0,41604	10	0,25687	1,8228
11	11	0,14712	1,82175	0,28765	11	0,10084	1,8228
12	12	0,11723	1,8186	0,27725	12	0,08272	1,8186
13	13	0,2386	4,73813	0,83526	13	0,16951	4,73813

Table 3 Short Circuit Current Data on The Main and Backup Relays of Scheme 1

Main Relay		Backup Relays	
1	3300	6	691
2	2890	1	2430
3	2530	2	2070
4	2240	3	1730
5	1850	4	1450
6	1520	5	1060
7	3330	12	734
8	2880	7	2420
9	2440	8	2040
10	2150	9	1640
11	1870	10	1400
12	1570	11	1110
1	3300	13	2620
7	3330	13	2610

The parameters used in the FA optimization process are configured as follows:

1. Randomization Parameter (α): 0.5
2. Attractiveness Coefficient (β): 0.2
3. Light Absorption Coefficient (γ): 1.0
4. Number of Iterations: 2500
5. Number of Fireflies: 50

These parameter values are selected based on prior research and are known to be effective for solving non-linear, multi-modal optimization problems within the context of protection coordination.

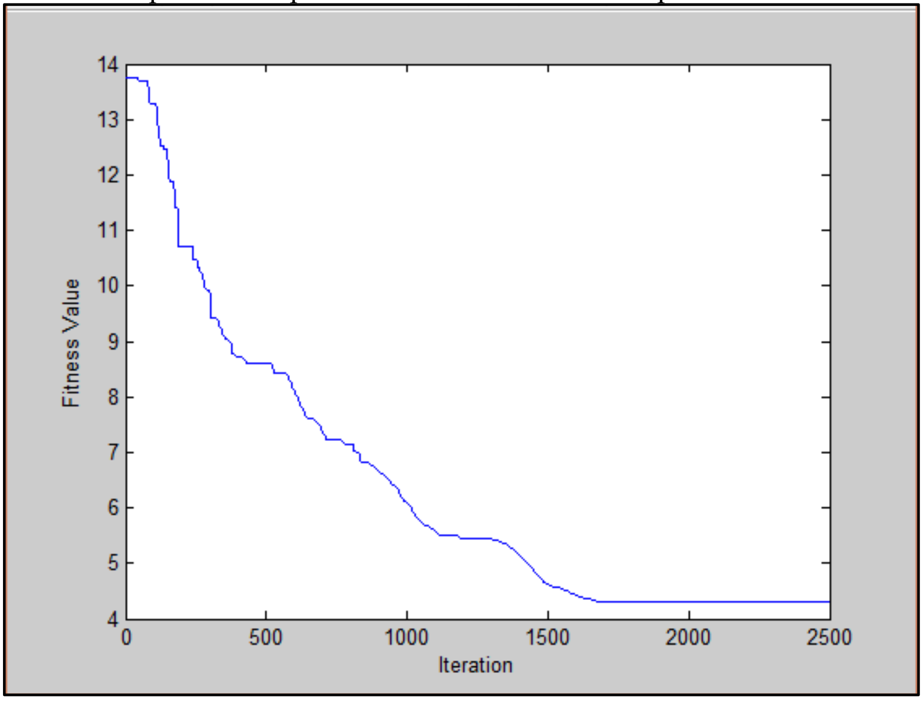


Figure 2. Convergence Curve Scheme 1

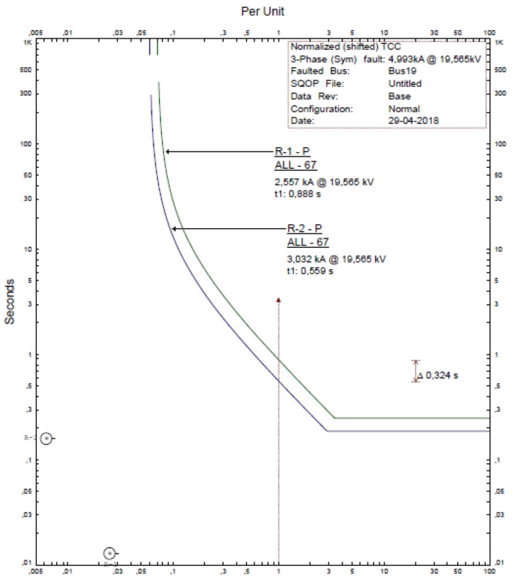
Figure 2 shows the fitness value convergence at iterations 1700 and 2000, reaching a value of 4.3077, which represents the total time taken for all operations in Scheme 1. Table 4 shows the TDS and Ipickup data based on the optimization results using the Firefly algorithm.

Comparison of Manual Calculation and Firefly Algorithm Result Curves

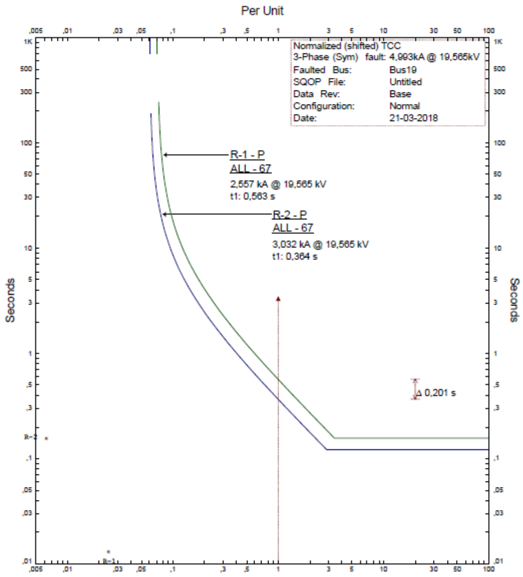
After manual calculations and optimization using the Firefly algorithm, the results will be simulated in ETAP to compare the operating time values. Figure 3a shows the TCC (Time Current Curve) curve from the manual calculation results, and Figure 3b shows the TCC curve from the Firefly algorithm in Scheme 1.

Table 4. TDS and Ipickup Generation Condition Scheme 1

Rele	Ipickup	TDS	TOP
1	1,8186	0,54436	0,42861
2	1,8207	0,42237	0,38338
3	1,8186	0,3166	0,33102
4	3,003	0,11772	0,24603
5	2,3919	0,10517	0,21083
6	3,717	0,04662	0,20371
7	3,717	0,23477	0,39822
8	2,3919	0,29626	0,36225
9	3,003	0,17149	0,32493
10	1,8186	0,2386	0,29764
11	1,8207	0,19011	0,27683
12	1,8186	0,14347	0,25375
13	4,73813	0,11148	0,59057



(a)



(b)

Figure 3a. TCC curve plot for relays 1 and 2 using manual calculations.
Figure 3b. TCC curve resulting from the Firefly algorithm in Scheme 1.

Based on the TCC plots shown in Figures 3a and 3b, it can be observed that the operating time obtained through Firefly Algorithm (FA) optimization is shorter than that obtained from manual calculations. Specifically, for Relay 2, the operating time with FA is 0.364 seconds, which is significantly faster compared to the manual method result of 0.559 seconds.

In Scheme 1, the TDS value for Relay 2 is lower, as the high fault current allows the primary relay to respond more quickly. The FA optimization dynamically adjusts the TDS values to minimize the relay operating time without compromising selectivity coordination. This results in a substantial reduction in operation time while maintaining reliable backup protection.

These results demonstrate the capability of the Firefly Algorithm to effectively adapt relay parameters in response to local fault current profiles, thus enhancing the overall responsiveness and efficiency of the protection system.

V. CONCLUSION

This study demonstrates that protection coordination optimization in a loop distribution system using the FA can produce more efficient relay settings compared to conventional manual methods. The faster relay operation time such as in Scheme 1 for Relay 2 (0.364 seconds versus 0.559 seconds) technically indicates the algorithm's ability to adjust protection parameters more precisely in response to fault current conditions. This directly enhances the protection system's responsiveness to faults and reduces the risk of equipment damage.

These findings suggest that the application of metaheuristic-based optimization methods like FA can improve the reliability of modern distribution networks, particularly those integrated with Distributed Generation (DG). In practical terms, this method has the potential to be implemented by power distribution companies to develop faster, more selective, and adaptive protection settings, serving as a foundation for future intelligent protection systems.

However, the scope of this research is currently limited to system simulations and has not yet been tested in real-world environments. Future work is recommended to evaluate the proposed method in real-time systems or to explore hybrid optimization approaches—such as combining FA with Particle Swarm Optimization (FA-PSO) to further enhance optimization performance and robustness.

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