Optimizing Power Management in Distribution Networks: A Mathematical Modeling Approach for Coordinated Directional Over-Current Relay Control

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***Abstract*—Optimizing Power Management in Distribution Networks through Coordination of Directional Over-Current Relays summarizes a study or project focused on enhancing the management of power in distribution networks by optimizing the coordination of directional over-current relays. Directional over-current relays are critical components of power distribution systems, designed to safeguard the network against over-current faults while maintaining operational stability. Proper coordination of these relays is vital to ensure that faults are isolated and cleared efficiently without causing extensive disruptions. In this paper, a mathematical modeling approach is employed to address the optimization of power management in distribution networks. This approach likely encompasses the development of mathematical models and algorithms that consider factors such as fault types, fault locations, network topology, and relay settings to improve the coordination of directional over-current relays. Here, different optimization algorithms have been implemented to optimize the operating time of relays & hence power management. Cuckoo Search Algorithm (CSA), Fire-Fly Algorithm (FFA), Harmony Search Algorithm (HSA), and Jaya Algorithm are employed to solve the coordination problem for directional over-current relays (DOCRs) with different test systems. The outcomes of this research may have practical applications in power distribution systems, potentially leading to more resilient and responsive networks that better manage power distribution and reduce disruptions during faults and outages.**

Keywords—Optimization; Cuckoo Search Algorithm (CSA); Fire-Fly Algorithm (FFA); Harmony Search Algorithm (HSA); Jaya algorithm; directional over-current relays

I. Introduction

The duty of protective systems is to detect fault and remove it from the power network. In all the processes, the time of operation plays an important role. The accuracy and reducing the execution time of the protective relay is the challenging part of the optimization algorithm. The most important elements that are used in power system for protection are distance relays and overcurrent relays. For protection of power system elements, protection scheme with primary and back up protection are used. In any power system, primary protective relays must function at the instant of fault occurrence to remove the faulty section; at the condition, whenever the primary protective relay is unable to perform, then the backup protective relay is supposed to operate. It should operate after a certain period of time for protection of power system from damage. The over-current protection relays are the frequently usable protection devices in the power system networks. For backup protection too, over-current relays are mostly used. But, the only protection scheme which provides the control to the power outages in some cases is the overcurrent protection. Unwanted relay tripping as a mal-operation for the backup protection relays has to be avoided. This is the major reason that over-current relay coordination in power system network is a major concern in protection system [1]. In the ring main distribution system for the management of power, the over-current relay coordination is a complex optimization problem with large number of constraints. The purpose is to find the minimum time of operation of primary relays as well as backup relays. It is to be noted that the mal-operation of relays is neglected during optimization. This results in making the problem more complex due to high number of constraints in modern day complex interconnected networks.

The optimum and accurate coordination of relays is necessary to recognize the fault efficiently within sort of time, to avoid possible outages and remove them from the power system network due to fault. The relay coordination problem is one of the most critical optimization problem because of large number of nonlinear constraints.

The motivation for this research stems from the growing importance of a robust, reliable, and efficient power distribution system. Modern society's increasing dependence on electricity, coupled with the advent of renewable energy sources, places new demands on distribution networks. The coordination of directional over-current relays becomes a vital consideration in ensuring that these networks can adapt to evolving conditions while continuing to provide a seamless power supply. Moreover, economic considerations drive utilities and power system operators to minimize downtime, reduce maintenance costs, and make efficient use of available resources. The potential benefits of an optimized relay coordination system are, therefore, multi-faceted, encompassing improvements in network resilience, safety, and cost-effectiveness.

Optimizing power management in distribution networks through the coordination of directional over-current relays offers a host of significant benefits. It enhances the overall reliability of power distribution, reducing service interruptions and downtime, which, in turn, leads to increased customer satisfaction and minimized economic losses. This optimization also contributes to greater safety by swiftly isolating faults and preventing potential hazards. Furthermore, it enables utilities to operate more efficiently, saving on maintenance costs and utilizing network resources effectively. With a more resilient and responsive grid, integration of renewable energy sources becomes smoother, reducing environmental impact. In summary, the benefits encompass improved reliability, reduced downtime, enhanced safety, cost savings, efficient resource utilization, and environmentally responsible power management, ultimately fostering a more dependable and sustainable energy distribution infrastructure.

Power distribution networks play a pivotal role in ensuring a consistent and reliable supply of electricity, making the coordination of directional over-current relays a crucial aspect of network management. The literature on optimizing power management through relay coordination reveals a growing body of research aimed at enhancing the performance of distribution systems. S. S. Gokhale et al [2] have discussed about the relay coordination and the importance of the optimization of relay operating time. The phenomenon of Cuckoo search algorithm has been discussed and applied to optimize the operating time of relays. Single end fed network power system with six overcurrent protective relays is considered as a test system for relay coordination problem. Chabanloo et al [3] have discussed the modified objective function and various characteristics of overcurrent relay and distance protection has been studied. The application of genetic algorithm, in order to solve optimization problem has been discussed. Mousavi et al [4] have discussed about the objective function minimization with constraints in this article. Constraints always affect the results and the operation time of the algorithm. The handling of constraints would be different for different optimization algorithms. Jagdish Madhukar Ghogare et al [5] have discussed radial and loop system coordinates with genetic algorithm. The different operators of genetic algorithm along with case study of symmetrical and unsymmetrical information set has been implemented. The relay coordination problem identification with their constraints has been studied and calculated for ten relay test system. Divya S Nair et al [6] have briefly discussed about the protective system and use of appropriate protective relays to protect the power system elements. The calculation of constraints and objective function parameters has been discussed with the help of fourteen relay system. The system is further optimized with genetic algorithm. The effect of relay operation time with different fault condition has shown in this paper. Abdul Wadood et al [7] have used the root tree algorithm (RTO), inspired by the random movement of roots, to search for the global optimum, in order to best solve the problem of overcurrent relays (OCRs). C.A. Castillo et al [8] have proposed the invasive weed optimization for the relays with non-standardized inverse time curves for improving overcurrent relay coordination performance. The model and implementation of optimization algorithm for coordination must be capable of handling increased problem dimension and constraints. Zahra MORAVEJ et al [9] have implemented the grey wolf optimizer algorithm and it has been used as an optimization tool to find optimum settings. Ahmed Korashy et al [10] have proposed a modified version for Water Cycle Algorithm (WCA), referred to as MWCA to effectively solve the optimal coordination problem of DOCRs. In the proposed technique, the search space has been reduced by increasing the C-value of traditional WCA, which effects on the balance between explorative and exploitative phases, gradually during the iterative process in order to find the global minimum.

The metaheuristic techniques are used on a daily basis for industrial planning, resource allocation, econometrics problems, scheduling, decision making engineering, and computer science applications. In this work, we have dealt with the comparative study of the different optimization techniques; namely, Cuckoo Search Algorithm, Firefly Algorithm, Harmony search algorithm and Jaya algorithm. These methodologies are applied for the coordination of directional overcurrent protective relays. The results obtained are validated when they accomplish all the constraints. The equality and inequality constraints show the coordination boundary for each and every primary and backup relay pair; which are having fault very near to the primary protective relays. The number of constraints will lead to an increase in the processing time of optimization process of any algorithm. For the small systems, it will take less time to get the optimum result, but in case of large systems, the number of constraints will increase leading to a large time for processing. If we reduce the constraints by neglecting them, the problem under consideration will not offer the appropriate results. For best results, the optimized value should follow the constraints religiously. Optimizing power management through the coordination of directional over-current relays brings about numerous implications, from immediate improvements in grid reliability and safety to longer-term economic benefits and environmental sustainability. These implications not only enhance the performance of power distribution networks but also contribute to the broader goals of energy sector efficiency, safety, and environmental responsibility.

Our paper is structured as follows: Section II highlights the basic function of relays and relay coordination in radial and ring main feeder system. Section III elaborates about the objective function and their constraints. Jaya algorithm is presented in Section IV, whereas, the different case studies have been discussed for different optimization algorithm and are presented in Section V along with the comparison of optimum results and their discussion with proposed Jaya algorithm. At last, Section VI provides the conclusion and remarks.

II. Directional Overcurrent Relay in Distribution Network

Directional Overcurrent Relays are devices which provide the protection against the interruption of the healthy supply system from the unhealthy fault situations. In the electrical power system, the coordination is the major factor because the devices are interconnected. Therefore, when fault occurs at certain point, it will definitely affect the entire system and can lead to major damage in the system. The solution of such a problem is solved by the coordination of relays. The least operating time can be achieved by using the optimization tools.

A. Coordination of Relays

Relay coordination is essential part of any protection system. When any network is protected with the distance relays, main and backup relay pairs are provided for each line. By arranging the overcurrent relays and distance relays, protection of lines gets expanded for better protection. If any disturbance occurs, at first, the primary distance (main) relay actuates. After that the overcurrent relay will be actuated. If this is unable to clear the fault, at a prior time and fails to actuate for any reason, distance relays will operate [11]. And, if it is also fails to operate, the backup protective overcurrent relay must immediately detach the faulty section from the network. As elaborated in Fig. 1 and Fig. 2, two constraints have to be added for coordination problems, as in (1) and (2) to create the sequential protection.

$$t_b\left(F_3\right)-t_{z2} \geq CI' \tag{1}$$

$$t_{z2}-t_m\left(F_4\right) \geq CI' \tag{2}$$

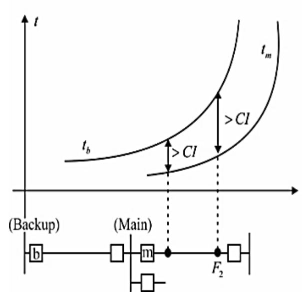

Fig. 1. Coordination of overcurrent relays.

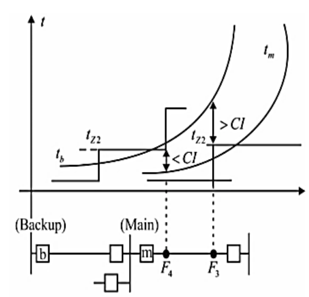

Fig. 2. Distance and overcurrent relay coordination.

Where, t_m is overcurrent relay operating time and the operating time of second zone protective relay ist_{z2}. At this condition when there is a new time interval for coordination (CI'); it should be defined between distance relays and overcurrent relays (not be the similar value as CI). This is used to establish the coordination of protective relay pairs

B. Over-current Relays Coordination in Radial Feeder System

Whenever the fault occurs, it is detected by both primary protective relays and backup protective relays. The operating time of relays, i.e., primary and back up is different, since the primary protective relay operating time is less than the backup protective relays, the primary protective relay will operate first. There is a radial distribution feeder system with two relays as depicted in Fig. 3. When fault occurs at point labeled as F, the relay R_B will operate first. Assuming the relay tripping time of relay $R_B$is set to 0.2 seconds, the relay R_A should operate after 0.2 sec plus CI. If the backup protective relay activates before the time of working of primary relay, it is called mal-operation [3].

Fig. 3. Simple radial feeder network.

C. Coordination of Over-Current Protective Relay in Ring Main Feeder Distribution System

It is essential to maintain the selectivity and sensitivity of protective devices at point A and B. The test system is presented in Fig. 4, which allows to maintain the supply to all connected loads at the condition of fault on any of the part of network and keeps the supply continuous [12]. Here, relay 1, and relay 8 are non-directional relays, apart from those, remaining relays are directional over-current relays (relay 2, 3, 4, 5, 6, and 7). All the directional relays are having their direction of tripping, which are away from the connected bus, shown in Fig. 4.

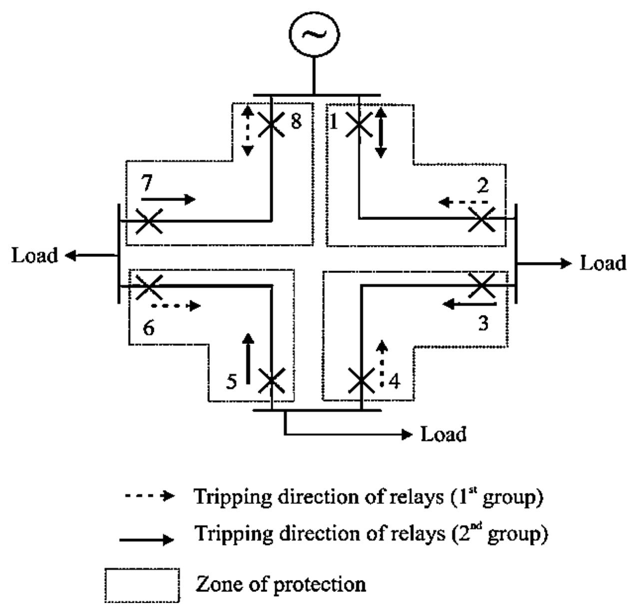

Fig. 4. A simple ring main feeder network (relay1 & 8 are non-directional and remaining relays are directional).

For the purpose of relay coordination, relay number 2, 4, 6, and 8 will make a group. Similarly, relay numbers 1, 3, 5, and 7 will form another group. Relay coordination has to be established from the relay 2, for group one.

The relay operating times has to take as $T_{R8} > T_{R6} > T_{R4} > T_{R2}$ for group one. Similarly, for group two, the relay setting initiates from relay 7. Operating time of relay has to take as $T_{R1} > T_{R3} > T_{R5} > T_{R7}$ for group two. The real operation time of relays has a constrained problem. The operating time should follow all the constraints for better selectivity and sensitivity of relay coordination. Since the size and complexity of the power system network goes on increasing, the number of constraints will increase and it becomes more complex problem to coordinate the relays.

III. Relay Coordination Optimization Problem

The ideal characteristics for IDMT relay shows that the operating time is inversely proportional to the fault current. Hence, overcurrent relay will operate fast after sensing a very large amount of current. However, IDMT relays are categorized into three types: standard inverse, extremely inverse and very inverse types. Relay characteristics depends on the type of standards selected for its operation. This can be defined by user or set by the ANSI, IEEE, IEC standards. Overcurrent relays are generally used for protection against inter phase faults and line to ground faults [13]. The operating time of the relay tracks the time over current curve, where the time delay be influenced by the value of current. There are two decisive factors, TDS and Plug Setting. The tripping time of the relay is closely related to TDS, plug setting and the fault current (I_f). The total operating time is given by a non-linear mathematical expression in (3) with respect to the constraint.

$$T = \frac{\alpha \times TDS}{\left(\frac{I_f}{PS \times CT_{pr}}\right)^{\beta}} - \gamma \tag{3}$$

α, β and γ are constants. According to IEEE standards [14], the values of these constants are given by 0.14, 0.02 and 1.0, respectively. I_f is the fault current at the primary terminal of current transformer (CT), where the fault occurs. CT_{pr} represents the primary of CT. The ratio between I_f and CT_{pr} provides the current sensed by the protective relay denoted by I_{relay} shown in (4).

$$I_{relay} = \frac{I_f}{CT_{pr}} \tag{4}$$

A. Relay Coordination Objective Function

The objective function is stated as the sum of operating times of all the primary relays expressed in terms of the product of Time dial setting (TDS) for each relay which is to be minimized, and a constant which is a function of ratio of fault current and pick up values of current. The inequality constraints framed according to close in fault and far end fault have the proper coordination margin for each primary/backup relay pair for a fault very close to relay pair.

To obtain the parameters of TMS and set I_{set_i}, the objective function and constraints of the problem is defined in (5) and (6) is given by

$$\text{Minimize} : \sum_{i=1}^{n} t_{op} \tag{5}$$

$$t_{op} = \left(TSM_i, I_{set_i}\right) = \frac{3TMS_i}{\log\left(\frac{I_{sc_i}}{I_{set_i}}\right)} \tag{6}$$

where n is the total number of protective relays,

t_{op} is the operating time of i_{th} relays,

TSM is the Time Setting Multiplier,

I_{sc_i} is the short circuit current,

I_{set_i} is the pre-fault current.

As in Fig. 5, a near end fault is a fault that occurs close to the relay and a far end fault is a fault that occurs at the other end of the line [15]. In directional over-current relays, the magnitude of the fault currents detected at different locations will be different. In Fig. 5, a radial feeder is shown which the simplest distribution system employing directional overcurrent relays R_primary and R_backup. Here, R_primary is the primary relay for the near end fault and R_backup is the backup relay for the same fault. The operating time of primary relay is T_primary for near-end fault and operating time of backup relay is T_backup which is greater than T_primary. Thus, the operating time of the backup protection should be equal to the operating time of primary protection plus the operating time of the primary circuit breaker.

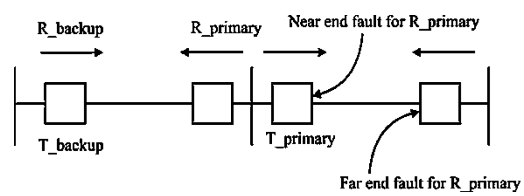

Fig. 5. Near end and far end faults for primary relay.

In coordination studies, the sum of the tripping times of all the primary protective relays to clear a near or far end fault can be considered as an objective function that is to be reduced. Therefore, the objective function to minimize (Z) can be expressed as given in (7).

$$\text{Minimize } Z = \Sigma_{i=1}^{N} T_{pri}^{i} + \Sigma_{j=1}^{M} T_{pri}^{j} \tag{7}$$

$$\text{where,} \quad T_{pri}^{i} = \frac{0.14 \times TDS^{i}}{\left(\frac{I_F^i}{\left(PS^i\right) \times CT_{pr}^i}\right)^{0.02} - 1} \tag{8}$$

$$T_{pri}^{j} = \frac{0.14 \times TDS^{j}}{\left(\frac{I_F^j}{\left(PS^j\right) \times CT_{pr}^j}\right)^{0.02} - 1} \tag{9}$$

$$i = 1, 2, 3 \ldots N; \; j = 1, 2, 3 \ldots n$$

where T_{pri} is operating time of the primary relay; CT_{pr} is the primary of CT and TDS is for Time Dial Setting for relay.

The essential constraints for optimization of relay coordination problem are given as in (10) and (11).

$$TSM_{\min i} \le TSM_i \le TSM_{\max i} \tag{10}$$

$$I_{load_i}^{Max} < I_{set_i} < I_{fault_i}^{Min} \tag{11}$$

The selection of TSM is used for each pair of main and backup relay (*m*, *b*). It is also used for errors regarding to zone of protection z_m. The failures are identified at the fault points. The operating time constraints give the range of operation of relays. The maximum and minimum value of fault current defines the pickup value of an overcurrent relay [16].

B. Constraints of Relay Coordination

Three constraints are considered for the minimization problem. The first constraint is TDS of the relay, which is the delay in time. Earlier the relay get operates each and every time the fault current becomes equal to or above the Plug Settings of relay (12).

$$TDS_{\min}^i \le TDS^i \le TDS_{\max}^i \tag{12}$$

i varies between 1 and N_i. $TDS_{\min}^i$ and $TDS_{\max}^i$ are the limits between minimum and maximum value of TDS allowed, which are 0.05 and 1.10 sec, respectively. The second constraint concerning PS takes the form (13).

$$PS_{\min}^i \le PS^i \le PS_{\max}^i \tag{13}$$

where i varies between 1 and N_j. $PS_{\min}^i$ and $PS_{\max}^i$ are the minimum limits and maximum limits of PS which are 1.25 and 1.50, respectively. Relay coordination functioning time is related to the fault current which can be seen by the protective relays and the pickup current setting. Relay functioning time is also depends on the category of the relay and it can be determined by standard characteristic curves of the relay or mathematical formula [2]. Hence, the relay operating time is defined by (14).

$$T^i{}_{\min} \le T^i \le T^i{}_{\max} \tag{14}$$

$T^i{}_{\min}$ is the minimum value and $T^i{}_{\max}$ is the maximum values for the relay operating time, which are 0.05 and 1.00, respectively. The organization time interval between the primary protective relays and the backup protective relays essentially verified during the optimization procedure. The coordination constraint between the primary and backup protective relays for relay coordination is given as (15).

$$T_{backup} - T_{primary} \ge CTI \tag{15}$$

where $T_{primary}$ is the functioning time of primary protective relays and T_{backup} is functioning time of backup protective relays. The minimum coordination time interval is shown by CTI. For electromechanical type of relays, CTI varies between 0.30 sec and 0.40 sec. Similarly, for numerical relays, the value of CTI varies between 0.10 sec and 0.20 sec. The value of T_{backup} and $T_{primary}$ can be determined by (16) and (17), respectively.

$$T_{backup}^i = \frac{0.14 \times TDS^x}{\left(\frac{I_F^i}{\left(PS^x\right) \times CT_{pr}^i}\right)^{0.02} - 1} \tag{16}$$

$$T_{primary}^i = \frac{0.14 \times TDS^y}{\left(\frac{I_F^i}{\left(PS^y\right) \times CT_{pr}^i}\right)^{0.02} - 1} \tag{17}$$

where T_{backup}^i is actuating time of the backup relay; $T_{primary}^i$ is actuating time of the primary relay; is the primary of CT and TDS is for Time Dial Setting for relay.

IV. JAYA ALGORITHM

The Jaya algorithm, proposed by Venkata Rao [17], is a global search-based population method. This algorithm is based on the concept that it always tries to reach the best solution and to avoid failure solutions. Moreover, it is easy to implement as it requires only common controlling parameters (population size and number of generations). The algorithms which fall under the category of evolutionary and swarm intelligence require proper tuning of specific parameters which are related to algorithm in addition to tuning of common controlling parameters. A change in the tuning of the algorithm specific parameters influences the effectiveness of the algorithm. The Jaya algorithm does not require any algorithm specific parameters and it only requires the tuning of the common controlling parameters for its working.

Step I: Declare all the design variables of the objective function. In the search space, generate the population size (N) which is random. Each variable in the population generated is a vector and there are n number of design variables and is given by (18)

$$x_{j=}x_{j,i}\left(l\right) + rand\left[0,1\right] \times \left(x_{j,i}\left(u\right) - x_{j,i}\left(l\right)\right) \tag{18}$$

$$i = 1,2,3\ldots.N;\ j = 1,2,3\ldots.n$$

Where $x_{j,i}\left(l\right)$ represents the minimum value and $x_{j,i}\left(u\right)$ represents the maximum value,

$rand\left[0,1\right]$ represents the generation of random numbers between 0 and 1, N represents the population size.

Step II: Set the number of iterations in the counter and let the iteration counter be F. Call the fitness function and update the population size while it reaches the number of iterations. Consider the G^{th} iteration and the absolute value of the candidate solution as $\left|x_{j,i,G}\right|$.

Step III: During the G^{th} iteration, let the variable generated be $x_{j,i,G}$ which is used to generate a vector $x^v{}_{j,i,G}$ corresponding to it. This value obtained should lie within the minimum and maximum bounds framed and can be given as (19)

$$x^{v}_{j,i,G} = \begin{cases} 2x^{l}_{j} - x^{v}_{j,i,G} & if\ x^{v}_{j,i,G} < x^{l}_{j} \\ 2x^{u}_{j} - x^{v}_{j,i,G} & if\ x^{v}_{j,i,G} > x^{u}_{j} \\ x^{v}_{j,i,G} & else \end{cases} \tag{19}$$

Step IV: The expression for the vector at the G^{th} iteration is given by (20)

$$x^{v}_{j,i,G} = x_{j,i,G} + r_{1,j,G}\left(x_{j,best,G} - \left|x_{j,i,G}\right|\right) - r_{2,j,G}\left(x_{j,worst,G} - x_{j,i,G}\right) \tag{20}$$

where $x_{j,best,G}$ and $x_{j,worst,G}$ represent the values of the variable j for the best and the worst candidate, respectively, $r_{1,j,G}$ and $r_{2,j,G}$ are the random numbers in the range [0,1],

$$r_{1,j,G}\left(x_{j,best,G} - \left|x_{j,i,G}\right|\right)$$

represents the term working towards achieving the best solution,

$$r_{2,j,G}\left(x_{j,worst,G} - x_{j,i,G}\right)$$

represents the term working towards avoiding the worst solution.

Step V: At the end, depending on the objective function, vector $x^{v}_{j,i,G}$ is compared to its corresponding variable $x_{j,i,G}$ and if it has lower value, it survives to the consecutive generation or else it will be retained in the population. Fig. 6 shows the flow chart of Jaya algorithm [4].

The flowchart of Jaya algorithm is demonstrated in Fig. 6.

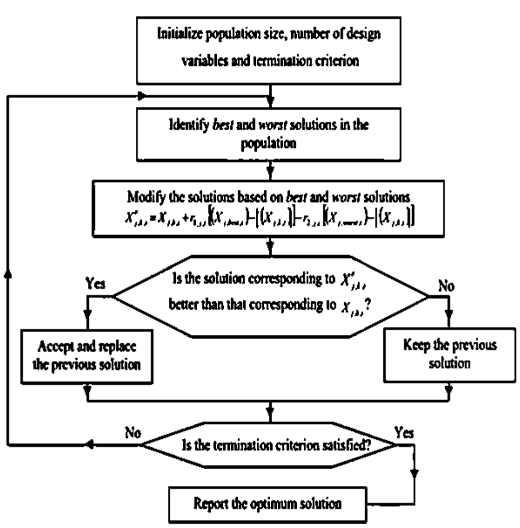

Fig. 6. Flow chart for Jaya algorithm.

The parameters of different optimization techniques used in this paper is listed in the Table I the number of iterations are kept equal for all the optimization techniques used [19, 20]. The algorithm parameters in the proposed method for optimizing power management through the coordination of directional over-current relays have a profound impact on the algorithm's performance and the outcomes of the optimization process. The choice of these parameters can significantly affect how quickly the algorithm converges to a solution and the quality of that solution. For instance, parameters related to learning rates, mutation rates, or step sizes can either expedite convergence or lead to overshooting the optimal solution if set too high, or slow down the process if set too low. The careful selection and tuning of algorithm parameters are pivotal to achieving effective and efficient power management optimization, ensuring robustness, scalability, and the ability to adapt to varying network conditions.

TABLE I. PARAMETERS OF OPTIMIZATION TECHNIQUES

CS Parameters	FF Parameters	HS Parameters	Jaya Parameters
Discovery Rate of alien eggs = 0.25 No. of nests:10 Iteration=10	No. of fireflies:100 Alpha = 0.5 Beta min=0.2 Gamma=1 Iteration=10	Harmony memory size=10 Harmony consideration rate=0.9 Minimum Pitch Adjusting Rate=0.4 Maximum Pitch Adjusting Rate=0.9	Population size=10 Run=10 Maximum fitness=100
Maximum Iteration:100	Maximum Iteration:100	Maximum Iteration:100	Maximum Iteration:100

V. ANALYSIS OF JAYA ALGORITHM

A. Analysis of 6-Bus, 10-Relays System

Single-line diagram of 220KV power system of Serum Institute, Pune India is shown Fig. 7 [18]. This is fed to Serum Substation 6 bus radial system. It has 10 relays, which is shown in Fig. 8. The short-circuit data are taken from the test data set. The CT ratio of 100/1 A is used for relay 1, 1000/1 A for relay 2, 300/1 A for relay 3 and 7, 500/1 A for relay 4 and 8, 600/1 A for relays 5, 6, 9, 10. The transformer rating for transformer T_1 has 400/220 KV, 315 MVA and %Z is 12.25%. Similarly for transformer T_2, 400/220 KV, 501 MVA, %Z is 12.25%, and for transformer T_3, 220/22 KV 30 MVA, %Z is 14.07%. Transmission line has double circuit line having lengths L_1 = 13.6 km, L_2 = 12.40 km; L_3 = 45 km; L_4 = 36 km; and line$L_{5,}L_{6,}L_{7,}L_8$ has length of 4 km. There are conductor spacing for vertical and horizontal line are 5.5 and 11 meters, respectively.

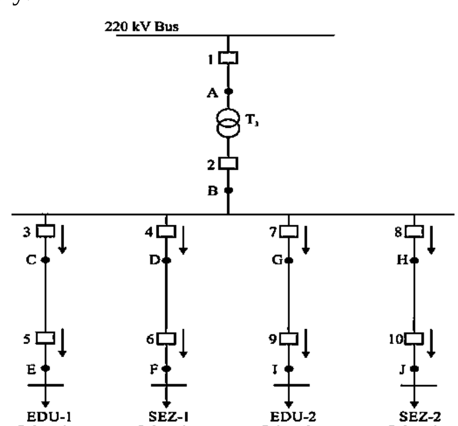

Fig. 7. Single line diagram of 6 bus, 10 relays test system.

The base MVA for calculating sequence currents is taken 500 MVA to construct sequence networks (positive, negative and zero). The load flow calculations are done with a conventional load flow analysis at all fault points based on those sequence networks. Primary and backup protective relay pairs are calculated and located in the system based on fault locations.

Table II demonstrates comparative analysis of some of the different nature inspired algorithms and the proposed Jaya algorithm. After the process of optimization, results in terms of relay operating time and total operating time for protective system given by some different algorithms. Minimum and maximum operating time limit has been set to 0.5 sec and 1 sec, respectively. Nineteen inequality constraint equations are formulated. The number of iterations would be same for all algorithms and is taken 100 iterations.

TABLE II. ANALYSIS OF 6 BUS, 10 RELAYS TEST SYSTEM FOR DIFFERENT OPTIMIZATION ALGORITHMS

Relay number	Relay operating time (sec)			
	Cuckoo search algorithm	Fire-fly Algorithm	Harmony Search Algorithm	Jaya Algorithm
1	0.2805	0.4106	0.0321	0.4160
2	0.1073	0.2875	0.0235	0.1791
3	0.3513	0.1846	0.0041	0.3949
4	0.3295	0.1941	0.0276	0.4514
5	0.2197	0.0488	0.0533	0.1997
6	0.3573	0.0417	0.0053	0.4840
7	0.0335	0.2060	0.0259	0.1893
8	0.4969	0.1695	0.1829	0.0986
9	0.0702	0.0488	0.1429	0.3402
10	0.2329	0.0417	0.1094	0.4547
$Z_{\min}$	3.3945	3.3148	1.5206	1.3383

Fig. 8 shows the comparative analysis chart of the 6 bus, 10 relays test system along their objective function results and respective optimization techniques.

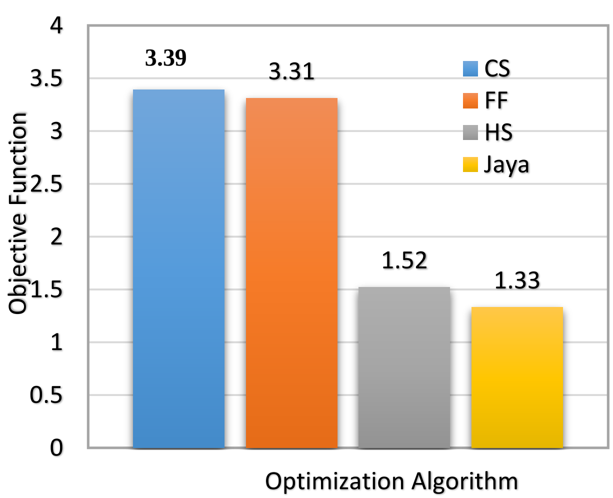

Fig. 8. Objective function values from various optimization techniques for 6 bus test system.

The results obtained from different optimization algorithms along the proposed Jaya algorithm using conventional relay characteristic are shown in Table II. The aim of the relay coordination optimization problem is to reduce the total time of operating for relays. Table shows the operating time of each relays, which can be comparable with the result from different algorithms. The overall total relay operating time has to be minimized. Proposed Jaya algorithm gives the best result among other algorithms. The evaluation time for each algorithm are different as per their parameters and number of populations. The number of population will increase the possibility to reach the most optimum solution, but it would also take more time to evaluation.

TABLE III. STATISTICALLY ANALYSIS OF 6 BUS, 10 RELAYS TEST SYSTEM

Parameter	CSA	FFA	HSA	JA
Mean	0.2479	0.1633	0.06070	0.3208
Standard Deviation	0.1456	0.1228	0.06227	0.1406
95% CI for the mean	0.1438 to 0.3520	0.07551 to 0.2512	0.01616 to 0.1052	0.2202 to 0.4214
Standard error of the mean	0.04603	0.03882	0.01969	0.01447

The statistical evaluation of the results obtained by different optimization techniques namely Cuckoo Search Algorithm (CSA), Fire-Fly Algorithm (FFA), Harmony Search Algorithm (HSA), and Jaya algorithm are presented in Table III. It shows the standard deviation and the standard error of the mean are 0.04603, 0.03882, 0.01969 and 0.01447 obtained by CSA, FFA, HSA and Jaya algorithm. From this table, it can be observed that the best value of standard deviation error is minimum (0.01447 sec) is obtained by Jaya which is the least value compared to the other techniques. This means that the Jaya algorithm gives the lowest standard deviation (0.01447 sec).

B. Analysis of for 8-Bus, 14-Relays System

The single line diagram for 8-bus test system is shown in Fig. 9 [1]. Which are contains 14 relays. There is also a link to additional network at various bus, as shown in Fig. 3, which are modeled by taking a base of 400 MVA for calculating the short circuit current. The short-circuit data for different fault conditions are obtained. The primary and back-up relay pairs are took from manual calculated short-circuit analysis and short circuit currents are calculated as per conventional load flow analysis. The CT ratio for relays 3, 7 9, 14 is considered as 800/5 A, for rest of relays CT ratio is considered is 1200/5 A. The population size is taken for a different algorithm is 10, and the number of iterations would be same for each algorithm, which has taken 100.

Comparative analysis of the various algorithms with the proposed Jaya algorithm is shown in Table IV. Finally the results in terms of relay operating time and TDS for main relays. Minimum and maximum operating time limit has been set to 0.5 sec and 1 sec, respectively. Twenty inequality constraint equations are formulated. The number of iterations would be same for all algorithms and is taken 100 iterations.

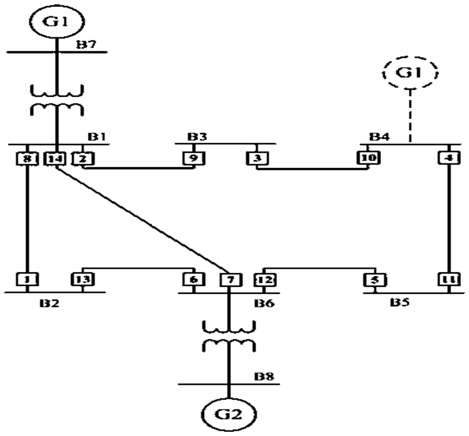

Fig. 9. Single line diagram of 8 bus, 14 relays test system.

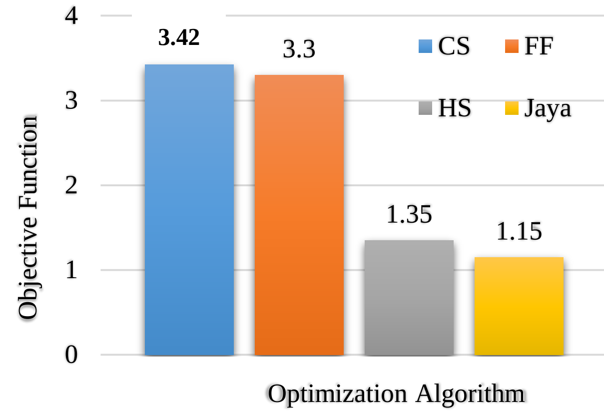

Fig. 10. Objective function values from various optimization techniques for 8 bus test system.

TABLE IV. ANALYSIS OF 8 BUS, 14 RELAYS TEST SYSTEM FOR DIFFERENT OPTIMIZATION ALGORITHMS

Relay number	**Relay operating time (sec)**			
	Cuckoo search algorithm	**Fire-fly Algorithm**	**Harmony Search Algorithm**	**Jaya Algorithm**
1	0.2805	0.4106	0.2186	0.0026
2	0.1073	0.2875	0.1111	0.0844
3	0.3513	0.1846	0.0600	0.0057
4	0.3295	0.1941	0.0319	0.0041
5	0.2197	0.0488	0.0901	0.1290
6	0.3573	0.0417	0.2315	0.2512
7	0.0335	0.2060	0.0024	0.0094
8	0.4969	0.1695	0.0390	0.0163
9	0.0702	0.0488	0.0874	0.0768
10	0.2329	0.0417	0.1343	0.0155
11	0.3212	0.3721	0.1173	0.2630
12	0.3432	0.3682	0.0014	0.1384
13	0.2981	0.2234	0.0450	0.0970
14	0.3357	0.3296	0.1846	0.0642
$Z_{\min}$	3.4233	3.3045	1.3553	1.1581

Fig. 10 shows the comparative analysis chart of the 8 bus, 14 relays test system along their objective function results and respective optimization techniques.

The results obtained from different optimization algorithms along the proposed Jaya algorithm using conventional relay characteristic are shown in Table IV.

The standard deviation and the standard error of the mean as shown in Table V are 0.03386, 0.03502, 0.01995 and 0.01339 obtained by CSA, FFA, HSA and Jaya algorithm. From this table, it can be observed that the best value of standard deviation error is minimum (0.01339 sec) is obtained by Jaya which is the least value compared to the other techniques. This means that the Jaya algorithm gives the lowest standard deviation (0.01339 sec).

TABLE V. STATISTICALLY ANALYSIS OF 8 BUS, 14 RELAYS TEST SYSTEM

Parameter	CSA	FFA	HSA	JA
Mean	0.2698	0.2090	0.09676	0.08269
Standard Deviation	0.1267	0.1310	0.07466	0.08751
95% CI for the mean	0.1967 to 0.3430	0.1334 to 0.2847	0.05365 to 0.1399	0.03216 to 0.1332
Standard error of the mean	0.03386	0.03502	0.01995	0.01339

C. Analysis of 14-Bus, 40-Relays System

The single line diagram of IEEE 14-bus test network is shown in Fig. 11 [21], which contains 40 relays. The short-circuit data are taken from the test data set. In this network, the system has 5 generators, 20 transmission lines and it is fed through two transformers T_1 and T_2. The power base of the system is 138 kV, 100 MVA. The range of TDS is set to be in between 0.5 sec to 1 sec for all the algorithms. The CT ratio is considered as 500/1 A for all the relays.

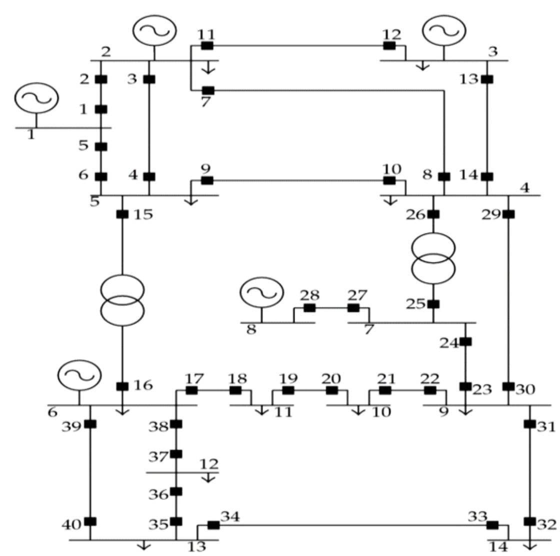

Fig. 11. Single line diagram of IEEE standard 14 bus test system.

TABLE VI. ANALYSIS OF 14 BUS, 40 RELAYS TEST SYSTEM FOR DIFFERENT OPTIMIZATION ALGORITHMS

Relay Number	Relay Operating Time (sec)			
	Cuckoo Search Algorithm	**Fire-fly Algorithm**	**Harmony Search Algorithm**	**Jaya Algorithm**
1	0.3464	0.2263	0.1016	0.0826
2	0.2205	0.2574	0.1112	0.0844
3	0.3156	0.3541	0.3101	0.1058
4	0.4366	0.3682	0.1320	0.0625
5	0.6594	0.5110	0.0901	0.1291
6	0.3882	0.2740	0.1640	0.0512
7	0.2874	0.2543	0.0625	0.0362
8	0.5520	0.5269	0.2390	0.1063
9	0.6306	0.5141	0.2875	0.1023
10	0.4336	0.4079	0.3344	0.1155
11	0.8722	0.3813	0.2873	0.2630
12	0.5683	0.3433	0.0215	0.0585
13	0.3235	0.2981	0.1050	0.0970
14	0.3297	0.3058	0.1847	0.0643
15	0.3934	0.3663	0.1986	0.0666
16	0.2905	0.2874	0.1112	0.0844
17	0.3176	0.2341	0.1601	0.0658
18	0.2926	0.1682	0.0320	0.0042
19	0.2394	0.2110	0.0901	0.1291
20	0.3506	0.2340	0.2315	0.2512
21	0.4360	0.3543	0.1025	0.0894
22	0.2596	0.2269	0.2390	0.1163
23	0.1236	0.1941	0.0875	0.0768
24	0.3365	0.4079	0.1344	0.0555
25	0.4692	0.3813	0.2173	0.1630
26	0.3695	0.3433	0.2015	0.1385
27	0.2235	0.2181	0.1450	0.0970
28	0.3296	0.3058	0.1847	0.0643
29	0.3342	0.2363	0.2186	0.0026
30	0.3369	0.2874	0.1112	0.0844
31	0.2365	0.2251	0.0601	0.0558
32	0.2125	0.1682	0.1320	0.0642
33	0.3265	0.2110	0.1901	0.1291
34	0.2785	0.1740	0.1315	0.0512
35	0.3696	0.2543	0.2025	0.0694
36	0.2365	0.2269	0.2390	0.1163
37	0.2874	0.3141	0.2875	0.2768
38	0.3355	0.2379	0.1334	0.1155
39	0.4364	0.3813	0.3173	0.2630
40	0.3652	0.3433	0.2415	0.1385
Z_{min}	8.3655	8.2506	4.5636	3.0454

The base MVA for calculating sequence currents is taken 500 MVA to construct zero sequence, positive sequence and negative sequence networks. The short circuit computation is completed with a conservative load flow analysis based on those sequence networks, at all fault points. Primary and backup protective relay pairs are recognized, and based on fault locations it is located in the system.

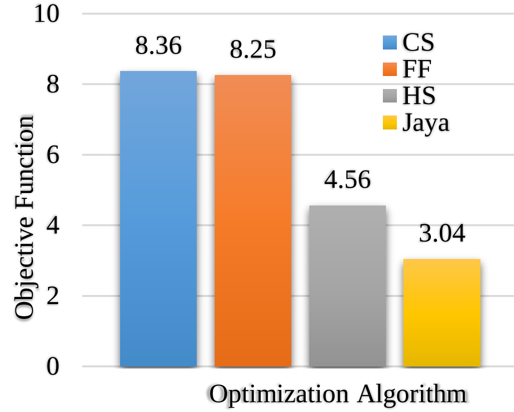

Fig. 12. Objective function values for various optimization technique for 14 bus test system.

Comparative valuation of the different present algorithms and the proposed Jaya algorithm is shown in Table VI. The output is shown in terms of relay tripping time and total operating time for primary protective relays given by some different algorithms. Minimum and maximum operating time limit has been set to 0.5 sec and 1 sec respectively. The number of iterations would be same for all algorithms and is taken 100 iterations. The population size is taken 10 for Jaya algorithm. Fig. 12 shows the comparative analysis chart of the 14 bus, 40 relays test system along their objective function results and respective optimization techniques.

TABLE VII. STATISTICALLY ANALYSIS OF 14 BUS, 40 RELAYS TEST SYSTEM

Parameter	CSA	FFA	HSA	JA
Mean	0.3638	0.3004	0.1708	0.1032
Standard Deviation	0.1387	0.09275	0.08119	0.06420
95% CI for the mean	0.3194 to 0.4081	0.2707 to 0.3300	0.1448 to 0.1967	0.08266 to 0.1237
Standard error of the mean	0.02193	0.01466	0.01284	0.01015

The standard deviation and the standard error of the mean as shown in Table VII are 0.02193, 0.01466, 0.01284 and 0.01015 obtained by CSA, FFA, HSA and Jaya algorithm. From this table, it can be observed that the best value of standard deviation error is minimum (0.01015 sec) is obtained by Jaya which is the least value compared to the other techniques. This means that the Jaya algorithm gives the lowest standard deviation (0.01015 sec).

D. Analysis of 30-Bus, 42 Relays Test System Network

The single line diagram of IEEE 30-bus test network is shown in Fig. 13 [13], contains 42 relays.

The short-circuit data are taken from the test data set. In this network, the system has 4 generators, 21 transmission lines and it is fed through 4 generators, two transformers T_1 and T_2. The range of TDS is set to be in between 0.5 sec to 1 sec for all the algorithms. The CT ratio is considered as 500/1 A for all the relays.

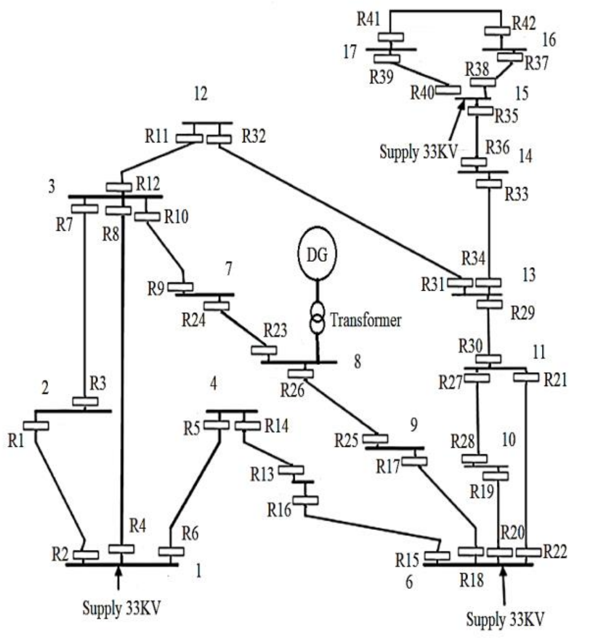

Fig. 13. Single line diagram of IEEE standard 30 bus test system.

Comparative valuation of the different present algorithms and the proposed Jaya algorithm is shown in Table VIII. The output is shown in terms of relay tripping time and total operating time for primary protective relays given by some different algorithms. Minimum and maximum operating time limit has been set to 0.5 sec and 1 sec respectively. The number of iterations would be same for all algorithms and is taken 100 iterations.

TABLE VIII. ANALYSIS OF 30 BUS, 42 RELAYS TEST SYSTEM FOR DIFFERENT OPTIMIZATION ALGORITHMS

Relay Number	Relay Operating Time (sec)			
	Cuckoo Search Algorithm	Fire-fly Algorithm	Harmony Search Algorithm	Jaya Algorithm
1	0.3364	0.1263	0.0516	0.0526
2	0.1205	0.1874	0.1112	0.0844
3	0.4156	0.3541	0.3101	0.1058
4	0.2366	0.1682	0.1320	0.0525
5	0.1594	0.2110	0.0901	0.1291
6	0.2882	0.0740	0.1640	0.0512
7	0.2574	0.1543	0.0625	0.0662
8	0.4320	0.3269	0.2390	0.0563
9	0.2906	0.3141	0.2875	0.1023
10	0.4336	0.4079	0.3344	0.1155
11	0.3722	0.3813	0.2873	0.2630
12	0.3683	0.3433	0.0615	0.0585
13	0.3235	0.2981	0.1050	0.0970
14	0.3297	0.3058	0.1847	0.0643
15	0.3934	0.2063	0.1986	0.0766
16	0.2905	0.2874	0.1112	0.0844
17	0.3176	0.2341	0.1601	0.0658
18	0.1926	0.0682	0.0620	0.0542
19	0.2394	0.2110	0.0901	0.1291
20	0.3506	0.1340	0.2315	0.2512
21	0.4360	0.3543	0.1025	0.0594
22	0.2596	0.2269	0.2390	0.1163
23	0.1236	0.1941	0.0875	0.0768
24	0.3365	0.4079	0.1344	0.0555
25	0.4692	0.3813	0.2173	0.1630
26	0.3695	0.3433	0.2015	0.1385
27	0.2235	0.2181	0.1450	0.0970
28	0.3296	0.3058	0.1847	0.0643
29	0.3342	0.2363	0.2186	0.0506
30	0.3369	0.2874	0.1112	0.0844
31	0.2365	0.2251	0.0601	0.0558
32	0.2125	0.1682	0.1320	0.0542
33	0.3265	0.2110	0.1901	0.1291
34	0.2785	0.1740	0.1315	0.0512
35	0.3696	0.2543	0.2025	0.0194
36	0.2365	0.2269	0.2390	0.1163
37	0.2874	0.3141	0.2875	0.2768
38	0.3355	0.2379	0.1334	0.1155
39	0.4364	0.3813	0.3173	0.2630
40	0.3652	0.3433	0.2415	0.1385
41	0.2874	0.2781	0.3150	0.0970
42	0.3125	0.3058	0.2747	0.0643
Z_{min}	9.6204	8.3520	5.5230	4.1308

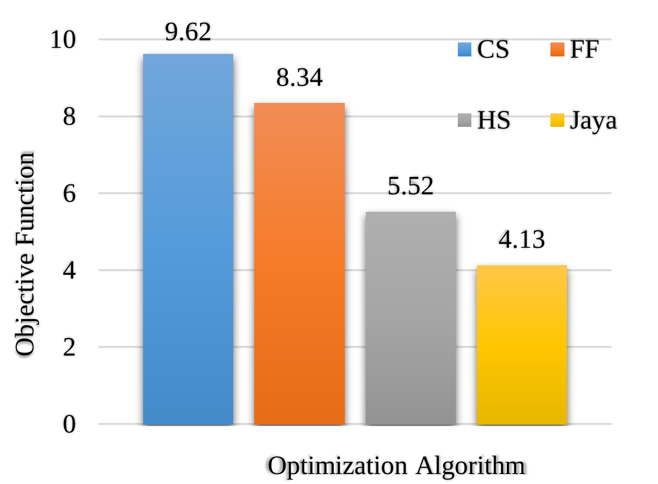

Fig. 14. Objective function values for various optimization techniques for 30 bus test system.

Fig. 14 shows the comparative analysis chart of the 30 bus, 42 relays test system along their objective function results and respective optimization techniques.

TABLE IX. STATISTICALLY ANALYSIS OF 30 BUS, 42 RELAYS TEST SYSTEM

Parameter	CSA	FFA	HSA	JA
Mean	0.3107	0.2588	0.1772	0.1011
Standard Deviation	0.08308	0.08744	0.08243	0.06194
95% CI for the mean	0.2849 to 0.3366	0.2194 to 0.3058	0.1515 to 0.2028	0.08181 to 0.1204
Standard error of the mean	0.01282	0.01349	0.01272	0.009558

The standard deviation and the standard error of the mean as shown in Table IX are 0.08308, 0.08744, 0.08243 and 0.06194 obtained by CSA, FFA, HSA and Jaya algorithm. From the above table, it can be observed that the best value of standard deviation error is minimum (0.06194sec) is obtained by Jaya which is the least value compared to the other techniques. This means that the Jaya algorithm gives the lowest standard deviation (0.06194sec).

The results obtained from different optimization algorithms along the proposed Jaya algorithm using conventional relay characteristic are shown in Table IX. The aim of the relay coordination optimization is to reduce the total operating time of all protective devices. Table shows the operating time of each relays, which can be comparable with the result from different algorithms. The value of objective function has to be minimized for relay coordination problem. Proposed Jaya algorithm gives the best result among other algorithms. The evaluation time for each algorithm is different as per their parameters and number of populations.

TABLE X. COMPARATIVE ANALYSIS OF RESULTS OBTAINED FROM DIFFERENT ALGORITHMS

Relay System	**Value of Objective Function (sec)**			
	CS	**FF**	**HS**	**Jaya**
10 relay system	3.39	3.31	1.52	1.33
14 relay system	3.42	3.30	1.35	1.15
40 relay system	8.36	8.25	4.56	3.04
42 relay system	9.62	8.34	5.52	4.13

Table IX shows the comparative analysis with optimized results of different optimization algorithms used for relay coordination optimization problem for four different test systems.

TABLE XI. STATISTICAL ANALYSIS OF OBJECTIVE FUNCTION

Parameter	CSA	FFA	HSA	JA
Mean	6.1975	5.8000	3.2375	2.4125
Standard Deviation	3.2653	2.8812	2.1191	1.4270
95% CI for the mean	1.0017 to 11.3933	1.2153 to 10.3847	-0.1344 to 6.6094	0.1418 to 4.6832
Standard error of the mean	1.6326	1.4406	1.0595	0.7135

The standard deviation and the standard error of the mean as shown in Table X are 1.6326, 1.4406, 1.0595 and 0.7135 obtained by CSA, FFA, HSA and Jaya algorithm. From this table, it can be observed that the best value of standard deviation error is minimum (0.7135 sec) is obtained by Jaya which is the least value compared to the other techniques. This means that the Jaya algorithm gives the lowest standard deviation (0.7135 sec).

Performance of the Jaya algorithm as the optimization tool for relay coordination operating time for different test systems has been evaluated. It has been observed that, the total sum of operating time of all the protective relays is given by the Jaya algorithm may be changed with the different evaluation, the number of constraints increases the overall evaluation time. It is also seen that some of relay TDS has been changed according to their parameters and limits of fitness, it would not much affect the overall operating time for relay coordination. It should be pointed that, the total operating time of all protective relays, is higher and for fault point at far-end when the fault is at the middle point, it is highest as compared to fault point at near-end, the proposed Jaya algorithm gives most appropriate results without any unbalanced operation of relays. It should also to be pointed that for the primary relays, relay operating time will rises as the change in the position of fault from near end to far end of the distributed feeders. The results undoubtedly indicate that the Jaya algorithm gives best optimum result as compare to the other algorithm used in relay coordination optimization.

VI. CONCLUSION

In this study, we have successfully developed and implemented a novel approach to optimizing power management in distribution networks through the coordination of directional over-current relays. Through our work, we have achieved several significant outcomes. First and foremost, we have demonstrated a practical and effective mathematical modeling approach that accounts for the dynamic nature of distribution networks, enabling precise and adaptive relay coordination. Our algorithm has shown promising results in terms of enhancing the reliability of distribution networks, significantly reducing downtime during faults, and improving the overall safety of the power grid.

The proper tuning of the algorithm specific parameters is a very crucial factor which affects the performance of the above mentioned algorithms. The improper tuning of algorithm specific parameters either increases the computational effort or yields the local optimal solution. The four different test systems are considered. The execution of each algorithm has been set to 100 iterations keeping the initial conditions as same for all the four test systems as considered in our test system. Jaya algorithm is considered as best one among the four algorithms based on the results obtained in the work. Jaya algorithm is found to be very efficient as we can see that the variation in the solutions on the reaching towards the optima. It should be noted that the total operating time of all protective relays is higher for fault point at far-end; when the fault is at the middle point, it is highest as compared to fault point at near-end; thus, the proposed Jaya algorithm gives most appropriate results without any unbalanced operation of relays in the distribution systems. It should also to be pointed that for the primary relays, relay operating time will rises as the change in the position of fault from near end to far end of the distributed feeders.

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