The Scientific Temper (2023) Vol. 14 (1): 165-171
E-ISSN: 2231-6396, ISSN: 0976-8653
Doi: 10.58414/SCIENTIFICTEMPER.2023.14.1.19
https://scientifictemper.com/
RESEARCH ARTICLE

Application of optimization algorithms in the development of a real-time coordination system for overcurrent relays

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Abstract

In this ongoing effort, optimization methods are being used to create a coordinated system for overcurrent relays that operates in real time. There are several potential methods for coordinating the overcurrent relays, but each has its own set of performance benefits that the others lack. This effort entails the development and evaluation of three separate algorithmic strategies in order to accomplish this goal. After using the GA (Genetic Algorithm) as a baseline for performance, the DE (Differential evolution) & ACO (Ant Colony Optimization) are programmed and equated to it. DE and ACO were preferred because their excellent performance were recorded across various types of literature, and since no one in the security industry had ever attempted to implement them. This resulted in their being deemed the most suitable adoptees. As the number of coordination pairs increased, GA produced the worst results, was the slowest and had the greatest influence on execution time. This was learned by examining the discrepancies between the three algorithms' outputs. Both ACO and DE, in contrast to GA, are much faster, provide better results, and are virtually immune to a rise in the number of coordination pairs.

Keywords: ACO, DE, GA, Optimization, Overcurrent Relays.

Introduction

One of the ultimate ideas that control our world is the notion of trying to improve one's situation as much as possible. For example, when the process of biological evolution is factored in, the biological concept known as "survival of the fittest" (1940) results in the better adaption of species to their respective habitats. An example of a species that has reached the stage in its evolutionary journey where it is able to outcompete all of the other creatures that live in its ecosystem is a local optimum. Homo sapiens have evolved to this point, and as a result, we now find ourselves in the position of having to share it with a wide variety of insects, germs, flies, cockroaches, and other unpalatable organisms. For as long as there are humans, the pursuit of perfection will be a driving force. Most people want to maximize their happiness while minimizing their efforts. For the sake of the economy, it is essential to maximize revenue and decrease costs. Therefore, optimization is a very ancient field of study with potential real-world applications.

Today, overcurrent relay coordination is an important issue in many types of networks. The methods have been laid forth. Because of their many advantages over traditional coordinating methods, strategies like these are often regarded as the best option. In a network, it is commonly understood that relays operate linearly and symmetrically; nevertheless, dial and I_{pickup} remain undefined. Thus, the objective function has introduced a nonlinear component to the problem. Manually coordinating hundreds of directed overcurrent relays in a meshed distribution system is time-consuming and labor-intensive. To accomplish online (real-time) coordination, it is necessary to develop an efficient and adequate optimization strategy.

Literature Survey

To conduct a thorough literature review, we have chosen the following works that are relevant to our investigation.

Abdelhamid, M. *et al.* (2021) suggested an upgrade to the Bonobo optimization method (IBO) to address the

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How to cite this article: Kamble, VS., Khampariya, P., Kalage, AA. (2023). Application of Optimization Algorithms in the Development of a Real-time Coordination System for Overcurrent Relays. The Scientific Temper, **14**(1):165-171

Doi: 10.58414/SCIENTIFICTEMPER.2023.14.1.19

Source of support: Nil

Conflict of interest: None.

Received: 12/01/2023 **Accepted:** 20/02/2023 **Published**: 25/03/2023

issue of directional overcurrent relays' (DOCRs') the best coordination. Power grid safety was impacted by this problem. It is a confined, problem of nonlinear optimization. IBO employs Levy flight distribution and three-leader selection (BO) to improve the original Bonobo optimization method. Two solutions for the DOCR were produced using BO and IBO. The 15-bus and 30-bus test systems were used because of the operating limitations to validate BO and IBO. The results of the BO algorithm and other well-known algorithms were compared to those of the IBO algorithm. The result indicated the superiority of the proposed IBO algorithm over current techniques in minimizing total relay operation time for optimal DOCR coordination.

Ahmadi, S. A. *et al.* (2016) investigated to find the Time Setting Multipliers (TSMs) by the evolutionary algorithm. They believed that the characteristics of overcurrent relays would aid TSM and coordination. Artificial intelligence was used to solve the coordination issue. The TSMs for the overcurrent relays were selected using the HSS method. The HSS result contrasted with an earlier study's genetic algorithm. Relay and HSS parameters in the simulation of a sample network demonstrate greater coordination.

Alam, M. N. *et al.* (2018) proposed a system for online adaptive protective coordination using a commercial AMPL-based IPOPT solver and numerical directional overcurrent relays (DOCRs). The suggested technique uses Intelligent Electronic Devices (IEDs) and a communication channel for real-time system information and relay settings. The provided technique may manage system losses of loads, generations, and lines. Miscoordination owing to Injections with DG are also managed. The IEEE 14-bus system was used to evaluate the proposed approach (with and without DG). The suggested strategy improved the dependability of the entire system by minimizing the amount of Energy Not Supplied (ENS). They had been contrasted with a SNOPT solver based on GAMS, an IPOPT solver based on OPTI Toolbox, an interior-point approach based on MATLAB, a metaheuristic genetic algorithm, and differential evolution. The recommended coordination approach benefits the adaptive protection system by producing outstanding outcomes quickly.

Alam, M. N. *et al.* (2016) proposed protective coordination techniques for directional overcurrent relays that use the interior-point method. Also, a novel objective function (NOF) was created to shorten the working hours of the backup and primary relays. Two test systems were used to evaluate the proposed solution methods and the objective function (one small and one large). The performance of the proposed method was compared to that of the genetic algorithm, differential evolution, and two-hybrid algorithms for the specified goal function. When various objective functions were examined in the literature, NOF's protective coordination results fared much better.

Al-Roomi, A. R. *et al.* (2016) developed a novel hybrid algorithm to solve the IEEE 6-bus test system that includes several additional sub-algorithms. They also studied numerically with electromechanical and numerical with static DOCRs. All studies in the literature, out of convenience, were limited to DOCRs that were numerical, static, or electromechanical. Instead of just throwing them, electromechanical or static relays can be used as a secondary line of defense. In the worst event, every bus would have two primary DOCRs. that would serve as DOCR backups for other buses. In other words, the problem's size has doubled., which makes it challenging to tackle effectively.

Asadi, M. R. *et al.* (2009) used a novel method for particle swarm optimization of OC relay coordination. They modified the OC relays' time setting multiplier (TSM) and plug setting multiplier (PSM). The majority of OC relays only accept discrete values, such as TSM and PSM, which changes the discrete form's final replies. In their method, the responses were quantized as part of the optimization process, producing TSMs and PSMs optimized for discreteness. The results were encouraging and shown to be a useful tool for organizing OC relays.

Bakhshipour, M. *et al.* (2021) proposed for the best overcurrent relay coordination, a novel data-driven protective logic from phasor measurement units (PMUs) has been developed. PMUs record positive sequence voltage across hundreds of miles at two substations apart, synchronized using a GPS satellite system. Control centers and/or substations collected the samples once the precise time tags had been inserted. Any node's where PMUs have been placed in the electrical grid, the phasor knowledge can be derived from these data. This allows for better state estimate, management, and protection. Besides current and voltage, phasor information was used in these relays to make decisions. The approach was tested on IEEE eight-bus and fourteen-bus networks.

Bedekar, P. P. *et al.* (2009) presented an approach for coordinating using a genetic algorithm (GA). of overcurrent (OC) relays. The objective was to create a perfect relay configuration that decreased relay operation time while preventing relay failure. In a ring-fed distribution system, OC relay coordination was improved using the GA technique. Constraints were added by penalizing the fitness function. Computer applications were created using the GA methodology.

Birla, D. *et al.* (2005) looked upon the problem of combining information from several sources with the aid of computers. When two security measures are deployed in succession and have features that offer a specific operational sequence, this is referred to as coordinated or selected. Modern linked power system networks have a significant challenge in the coordination of directed overcurrent relays. There have been numerous attempts to automation of the relay coordination procedure. This article outlines key accomplishments in the coordination of time-overcurrent relays utilizing diverse strategies and procedures. Future researchers will be able to find relevant references thanks to our work.

Bottura, F. B., *et al*. (2014) demonstrated a Hybrid Genetic Algorithm (HGA) for the coordination of directional overcurrent relays in a real mesh power system, a component of Brazilian power transmission network. The HGA employs a combination of linear programming and genetic algorithms to determine optimal relay settings. The operating time of relay was reduced through successful cooperation. The power system was simulated for short circuit studies using CAPE software. Discrete Particle Swarm Optimization (DPSO), a modified version of traditional particle swarm optimization, is used to compare the HGA solutions to its output. Last but not least, the DPSO asserts that HGA produces outstanding outcomes for coordinating the overcurrent relays in the test system.

Bouchekara, *et al.* (2016) used the Backtracking Search Algorithm (BSA), a novel metaheuristic approach, to address the coordination issue of the DOCR.. The coordination problem is an optimization challenge for all major relays. Three test systems—the 6 bus, 8 bus, and 15 bus—have been used to evaluate the proposed methodology. Moreover, a reliable approach for contrasting the results of the proposed BSA with those of other well-known metaheuristics has been developed. BSA performs better in DOCR coordination problems than other methods.

Chabanloo, R. M. *et al.* (2011) introduced a fresh objective function (OF) for the evolutionary algorithm (GA) approach to solve the optimization problem of coordination of distance relays and overcurrent relays. As a target performance, O/C relay coordination was updated, and distance relay coordination was added as a target function. To achieve the best coordination, GA analyses a variety of O/C relay features. On two power system networks, the strategy was tried.

Chelliah, T. R. *et al.* (2014) produced and put into use an opposition-based chaotic differential evolution is a pair of algorithms (OCDE1 and OCDE2). Directional overcurrent relay coordination (DOCR) was approached by the developers as an optimization problem and was dealt with using various optimization techniques. To address these problems, numerous algorithms have been developed over the years. Both types used a chaotic scale factor and opposition-based learning for the optimum outcome. Four circumstances were used to test the strategy. They evaluated the results against previously proposed algorithms in the literature and discovered that the suggested tactics were effective.

Costa, M. H. *et al.* (2019) presented A new approach to enhance the resilience coordination of the directional overcurrent relay. The expected relay parameters were initially found using a computational method based on Differential Evolution, local search techniques, and linear programming. As opposed to that, when a single line dropped, the algorithm's response was used as an input to a re-optimization framework to reduce unwanted load shedding (N-1 criterion). An interconnected network, an IEEE-30 bus, IEEE-118 bus, and IEEE-300 bus were used to test the technique. There were 1044 primary/backup connections and 590 relays.

In the present investigation, we will apply three optimization techniques to over-current relays and find the best optimization technique for over-current relays.

Relay's Real-Time Coordination

The real-time method is all about obtaining information on the most current changes that have been made to the components and the network. This is the most important aspect of the real-time approach. This is what the technique is all about. These modifications provide the basis for the computation of input data for posterior relay coordination. They serve as the foundation. It is said that the hardware system required for online updates has already been constructed; at this point, the only thing that needs to be done with the hardware is to program it with an acceptable real-time algorithm. The following is an example of a thorough explanation of the procedure, which you may find: Once the system has been brought up to date, any newly added components or changes to the network settings will be reflected in the data that is saved inside the system. After then, the Y_{bus} is either redesigned from scratch or updated based on the data that was acquired by utilizing the Incident strategy and the Inspection technique in reverse order. One of these two options is chosen after the conclusion of the investigation. After this step has been finished, automated creation of the lists of "Relay Names" and "Coordination Pairs" will be carried out. After that, the Z_{bus} is either completely recreated from the ground up or updated using the Block building technique and the Partial Inversion Motto. After the process, a fault analysis is carried out using either Symmetrical Components or Thevenin's method, depending on the strategy that was used to solve the problem. This will have occurred after all the steps that came before it has been completed. This will have been done in order to maximize the efficiency with which the algorithm works. This is going to be done so that the best possible topology for the network may be identified. The execution of these processes will, in a short amount of time, improve the network's operational capabilities. A representation of this concept is shown in Figure 1, which the reader may find helpful.

The simulation is carried out for n different types of

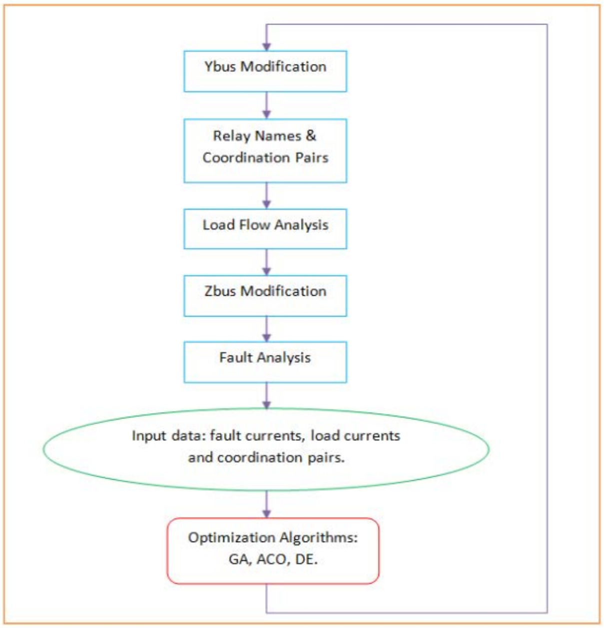

Fig.1: Comprehensive view of the real-time coordination flow diagram.

conceivable structures and one extra sort of structure. Not only does data about coordina tion contain the maximum load, but it also includes the fault currents. This technique first filters the relay's sensitivity before relaying the data to overcurrent relay optimization procedures. It guarantees that every possible combination is synchronized. Consequently, optimization algorithms won't waste time attempting to build insensitive relay pairs with no parameters that are suitable for usage.

$$Sensitivity = \frac{I_{sc2\emptyset\ backup}}{k \times I_{Load}} \quad (1)$$

Where k is equal to 1.4, which is the minimum value that may exist inside the parameters of [1.4, 1.6], the range that is being used. Therefore, relays that cannot satisfy the sensitivity criteria will be filtered out, even if they are using the most stringent possible value of k. The connection between the current running through some kind of two-phase short circuit and the current flowing through the relay's pickup coil is referred to as the "sensitivity" of the relay. The current running through a two-phase short circuit should be at a minimum 1.5 times larger than the current flowing through the pickup if the sensitivity is acceptable.

Motoes Of Optimization Algorithms

It is of the utmost importance to formulate the optimal solution that will be applied to assess the adequacy of the settings. Appropriateness can also be referred to as the capacity of a setting to meet the needs of a criterion. Developing the fitness function that will be utilized to analyze appropriateness is of the utmost importance. This fitness function has the ability to be the sum of a very large number of distinct goal functions from other domains. This fitness function has a direct influence on the final product that is produced as a consequence of the optimization approaches. A criterion is required to give data concerning if the result of the configurations is inappropriate (outside of the satisfaction limit), satisfied (within the satisfaction limit), or the optimum outcome for the settings to be rewarded or punished before the analysis of the settings in the objective function can take place. The indicator must provide this information well before the analysis of the settings in the objective function. This information is needed to determine whether the settings should be rewarded or punished. In the case that the relays need to be coordinated, this indicator is the time, and it is referred to as the CTI. First things first: it is necessary to examine all of the configurations of every relay that is part of the population. For the sake of this evaluation, equation 2 will be applied to both the primary and secondary relays ($t_{primary}$ and t_{backup}, respectively). The short circuit current is the sole piece of data that is different between the backup and primary relay at this point. It is necessary to subtract the primary time from the backup time so that an accurate CTI calculation. This can be seen in equation (2).

$$CTI_{real} = t_{backup} - t_{primary} \quad (2)$$

This limitation is imposed by the relays. Afterward, use the actual CTI that was measured and deduct the CTI that was stated beforehand to arrive at the signal, which is expressed by the formula that is provided below Equation (3).

$$CTI_{indicator} = CTI_{real} - CTI_{pre-specified} \quad (3)$$

The CTI indicator will reveal whether the settings are poor (dropping outside of the satisfaction limit), superb (dropping inside the satisfaction limit), or ideal, and the user will be able to choose if they should be rewarded or penalized before entering the target function based on this information. Inaccurate CTI readings result from the process of subtracting two separate CTI readings from one another. If the error is 0, then the settings are excellent; nevertheless, this scenario is relatively rare, and as a consequence, the large majority of relays do not support it. No kind of discipline should ever be administered. If the mistake is not positive, the settings are either perfect or adequate; nevertheless, the delay is far greater than what was mentioned in the beginning. This has to be penalized to get closer to zero errors (meeting the pre-specified CTI). Negative mistakes are what lead to a loss of coordination, and the sole way to stop this from happening in the first place is to punish negative mistakes severely.

The following equations describe the boundaries of the relay settings:

Finding out the total number of synchronized CTI fault pairs, the entire duration of time spent in primary and

$$dial_{min} \leq dial \leq dial_{max} \quad (4)$$

$$I_{Pickup\ min} \leq I_{Pickup} \leq I_{Pickup\ max} \quad (5)$$

standby operations, and the overall number of violations are the goals purposes of this effort. Three algorithms are being considered for this problem, i.e. (DE, ACO, and GA). Everyone makes use of this target function in some capacity while doing their own particular computations. It is shown in eq. (6).

$$fitness = \left(\frac{NV}{NCP}\right) + \left(\frac{\sum_{a=1}^{NCP} t_{principal_a}}{NCP}\right) * \alpha + \left(\frac{\sum_{b=1}^{NCP} t_{backup_b}}{NCP}\right) * \beta + \left(\sum_{l=1}^{NCP} E_{CTI_L}\right) * \delta \quad (6)$$

Vi. Ga, Aco, And De: Comparison

In this part, the performance of each algorithm is evaluated by utilizing the IEEE 14-bus test system. Each algorithm's positive and negative aspects are brought to the reader's attention. Their performance is determined by the amount of time it takes to execute each algorithm, which ultimately determines its quality, resilience, and capacity to converge.

It is possible to condense the search area by repeatedly putting the test system through its paces and analyzing the outcomes, which will eventually result in more accurate findings and more rapid convergence of the algorithm. All three GA, DE, and ACO have settings for continuous dial and k at their disposal. As the step size grows more continuously, the AS graph widens, and the amount of time necessary to do the work also rises (smaller). Because of this, dial and k were chosen for real-time coordination based on the information that was supplied in Table 1. Before making this decision, it was ensured that they were neither extremely large nor excessively small. This was done to ensure that the results were accurate. The procedure will be terminated when the number of times through the loop exceeds one thousand. To make it easier to compare the different approaches, the halting conditions of each one was removed. This maximum number of iterations was chosen because, in comparison to 3,000 and 5,000 iterations, the progress in algorithms is not as evident after 1,000 iterations as it is after those earlier thresholds. A combined total of 500 agents are used in the simulation of the GA, DE, and ACO scenarios. Speed was the primary factor in determining the number of persons and agents participating.

Table 1: GA, ACO, and DE: Parameter Setting

Parameters	GA	ACO	DE
CTI	0.3	0.3	0.3
dial	[0.5:2.0]	[0.5:2.0]	[0.5:2.0]
k	[1.4:1.6]	[1.4:1.6]	[1.4:1.6]
dial step	continuous	0.05	continuous
k step	continuous	0.01	continuous
Q	--	100	--
R	--	5	--
r	--	--	0.5
F	--	--	0.8
Cr	--	--	0.5
individual-ants	500	500	500
iterations	1000	1000	1000

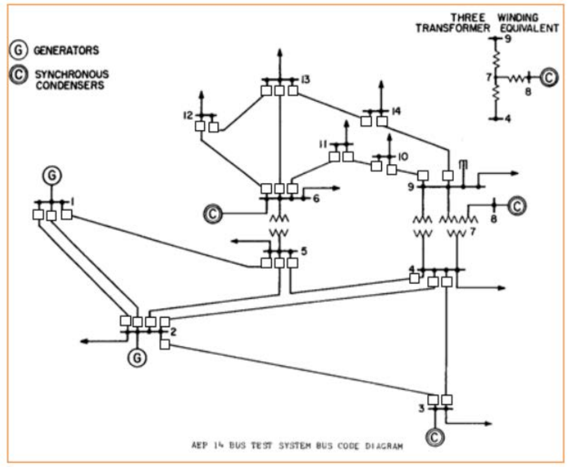

Fig.2: Test system

The System's Data Testing

An IEEE Fourteen bus test system was employed to examine and evaluate as well as compare and contrast the performance of the three techniques. The complete configuration of the system is shown in Figure 2. It was determined that the voltage on the buses that were linked to the high voltage side of the transformers would be 34.5 kV, while the voltage on the buses that were connected to the low voltage side of the transformers would be 22 kV. As can be seen in Table 1, it is often believed that all relays have a time characteristic curve that is very inverted. This theory is supported by the data shown in the table. The names of the relays are not assigned in the form of numbers, as was the norm in the past; rather, the real-time algorithm produces them automatically in the form of a string of numbers. Traditionally, the procedure included allocating the names of the relays in the form of numbers. The names of these relays, which are a string of numbers, each have three digits that make up their entirety. The first number indicates the name of the bus that is situated in the immediate vicinity. The second digit represents the name of the bus that is situated farther away, and the number of lines that run in parallel between the two buses is denoted by the third digit. For instance, the relays that connect buses 1 and 2 and are situated near bus 1 are represented by the notation [1 2 1] and [1 2 2], and the relays located near bus number 2 are represented by the notation [2 1 1] and [2 1 2] respectively. Other examples include the relays that connect buses 1 and 3 and are located close to bus 3, which are denoted by the notation [3 1 1] and [3 1 2]. Additional examples are the relays that link buses 1 and 2 and are positioned near to bus 2. These relays are represented by the notation [1 2 1] and [1 2 2] and are situated close to bus 2.

The two lines that link buses one and two have had their impedances tested, and the results showed that they both had the same value. Hence, the relays [1 2 2], [1 2 1], and [2 1

1] all feel the same maximum load currents, which is 815 A. This is because all three relays have a common grounding. This is due to the fact that the grounding for all three relays is shared. While operating at their full capacity, these relays are able to withstand load currents of up to 1,849 A. This is still the case despite the fact that all triple relays, [1 2 1], [1 2 2], and [2 1 1] detect an identical number of maximum load currents. The present figures were produced through an operation that tried to place as little of a strain as humanly feasible on the participants. In order to compute the leakage current, you need to open up the circuit all the way to its far end. This was done for two reasons: the first was to get the greatest over current that the relay detects, and the second was to limit the possibility that the remote end relay would malfunction. The first reason was to acquire the maximum overcurrent that the relay detects. Both of these reasons led to the decision to do this. Both of these factors contributed to my arrival at this conclusion. It is important to remember that the load flow and fault analysis will need to be recalculated using a real-time method if the operation of components or the network's topology is changed. For generator one, the value of the data X_d is 0.01, while the value for generator two is 0.3. The data from the first 14 bus loads are equivalent to the maximum load, while the data from the first 14 bus loads only account for 70% of the minimum load.

Result And Discussion

A total of sixty-two relay coordination pairs are active inside the 14-bus testing system located before the sensitivity filter. Despite this, this may change depending on how the load need evolves over the course of time. The simulation of the test system is accomplished by using DE, ACO, and GA with pertinent constraints that were described in the part that came before this one. This is carried out at a time when the load is at its utmost. With the application of the sensitivity filter, there are a total of thirty-nine distinct relay coordination pairs available for use. A total of ten iterations were simulated using each of the three different approaches. The level of convergence achieved by each method was evaluated by performing 10 simulations and averaging the results of the iteration that achieved the highest level of fitness overall. To facilitate comparison, this is depicted in Figure 3.

The following data is shown in Table 2: the average number of coordination constraint violations; the average rate of fitness convergence; and the average amount of time needed for GA, ACO, and DE, respectively.

Given these facts, it is possible to conclude that ACO and DE are superior to GA in terms of the level of convergence they achieve, the speed at which they execute, and the many coordination limitations they violate. It is essential to take note that in ACO and DE, each coordinating pair is coordinated for all 10 simulations. This is something you should keep in mind. In contrast hand, not every one of the 10 different GA simulations has coordinated action between all of the coordinating pairings. The DE delivers a very powerful and effective performance. Table 3 shows the relay settings and operation time that have been averaged, as well as the CTI and sensitivity values for the 10 simulations that have been averaged using GA, ACO, and DE.

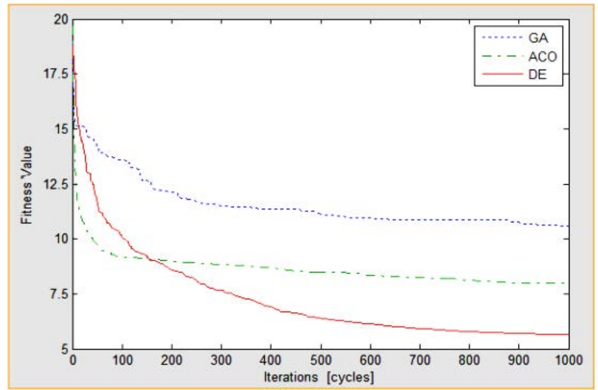

Fig.3: Average fitness convergence.

The lowest dial value is used by many relays, which ultimately leads to the relay being conducted for a shorter period of time. This is even though Table 3 reveals that the average dial is rather near to the value 1. Other relays use a dial that is quite near the minimum, but the remaining relays use bigger dials since coordination requires larger dials. The fact that each relay has a relatively small k contributes to the system's greater sensitivity. This realization applies to GA in addition to ACO and DE.

The results that were provided by each of the three algorithms demonstrated that they could produce results that might be regarded as realistic for the system being investigated. GA ended up having results that were below average, while at the same time, DE demonstrated that they had an excellent performance. The DE algorithm is the quickest of the three and provided the greatest outcomes when tested with 500 different individuals. The Department

Table 2: A comparison of the outcomes that GA, ACO, and DE achieved on average when at maximum load.

Parameter	GA	ACO	DE
NV	0.1	0	0
Fitness	10.611	7.994	5.598
Time(sec)	5507	441	89

Table 3: Average relay parameters at maximum load.

Algorithm	Dial	K	Backup Time	Primary Time	CTI	Sensitivity
GA	1.1324	1.4952	3.1425	1.1817	1.9650	3.12005
ACO	0.9875	1.5004	2.3968	1.0383	1.3584	3.12624
DE	0.7374	1.4289	1.7015	0.7346	0.9669	3.29381

of Energy (DE) is the organization that has the highest level of expertise required to successfully carry out the tasks associated with real-time coordination. In certain situations, real-time coordination made the DOCRs much more sensitive than they were before, but in other situations, it made the DOCRs much less sensitive than they were before, which was a significant change. The effect of real-time coordination varied depending on the circumstances. The DOCRs were responsible for the occurrence of both of these effects. When some requirements are satisfied, the amount of time necessary for the relay to operate is decreased; yet, when other conditions are met, the amount of time that is required to make the relay work is raised. These issues can be traced back to the planning and building processes that went into creating the network.

Nevertheless, these shifts, which may include a decrease in sensitivity or an increase in the length of time it takes for a relay to function, result from the most recent condition in which the network is operating. This could mean that the sensitivity is reduced or that the amount of time it takes for a relay to function increases. As a result, the system is ready to deal with another scenario that no one could have anticipated. Because of this, system was always capable of maintaining its strength regardless of any changes that could have occurred at any time.

Conclusion

It is concluded that as the coordination pairs increased, GA produced the worst results, had the slowest execution time and had the most influence on the total execution time. The answer to this question was found by comparing the outcomes produced by the three different algorithms. On the other hand, ACO and DE are both much faster than GA, provide better results, and are essentially unaffected by an increase in the total number of coordination pairs. In this specific piece of research, the amount of time invested in execution is a very relevant factor, along with the resulting quality, durability, and capability to converge. DE has the best overall performance of all the algorithms investigated for this paper. This is the case when compared to the other algorithms. Real-time coordination was used, which helped verify the theory's correctness. The length of time the relay is permitted to work is decreased, the system's sensitivity is increased, and preparations are made for another emergency.

Acknowledgment

The primary author would like to express gratitude to his research guide, Prof. Dr. Prabodh Khampariya, of the Electrical Engineering Department in the School of Engineering at SSSUTMS in Sehore, and to his co-guide, Prof. Dr. Amol A. Kalage, of the Electrical Engineering Department at SIT in Lonavala, Pune, for their technical assistance.

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