An-Najah National University

Faculty of Graduate Studies

# A HYBRID FIREFLY-GENETIC ALGORITHM FOR THE OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS

By

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# Dedication

This research is dedicated to:

My great parents, who never stop giving of themselves in countless ways;

Our friends and colleagues who support us through all obstacles and issues;

An-Najah National University; my second magnificent home

The dear supervisor Dr. Maher Khammash on their generous efforts in the service of this study.

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# Declaration

I, the undersigned, declare that I submitted the thesis entitled:

# A HYBRID FIREFLY-GENETIC ALGORITHM FOR THE OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

**Student's Name:** Tareq Husam Foqha

**Signature:**

**Date:** 19/02/2023

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# Abstract

**Theoretical background:** Directional overcurrent relays are applied for power system protection to ensure safe, reliable, and efficient operation. The coordination of directional overcurrent relays is non-linear and highly constrained optimization problem. The main goal of the optimization is to minimize the summation of operating times of primary relays, by setting optimal values for decision variables as time multiplier setting (TMS) and plug setting (PS).

**Aims:** The main objective of this research is to develop a hybrid optimization algorithm which consists of modified firefly algorithm and genetic algorithm to find better solutions.

**Methodology:** First, this study modified the original firefly to obtain a global solution by updating the firefly's brightness and to avoid the distance between individual fireflies from being too far. Additionally, the randomized movements were controlled to produce a high convergence rate. Second, the optimization problem is solved using standard genetic algorithm. Finally, the solution obtained from the modified firefly algorithm is used as the initial population for the standard genetic algorithm. The modified firefly algorithm, genetic algorithm and hybrid firefly-genetic algorithm have been tested on IEEE 3-bus, 8-bus, 9-bus and 15-bus networks.

**Main Results:** The results indicate the effectiveness and superiority of the proposed algorithms in minimizing the overall operating time of primary relays compared to other algorithms mentioned in the literature for directional overcurrent relays coordination.

**Conclusion:** Compared to modified firefly algorithm and standard genetic algorithm, the proposed hybrid algorithm has minimized coordination interval time between primary and backup relay pairs.

**Keywords**: Directional overcurrent relays optimization, Hybrid algorithms, Firefly algorithm, Genetic Algorithm.

# Chapter One

# Introduction and Theoretical Background

## 1.1 General Background

Because of the accelerated expansion of the distribution electric power networks resulting from increasing consumer consumption and the requirement for more reliable service that meets regulatory standards, the distribution electric power system requires robust and effective protection system [1]. The distribution system is mainly protected by overcurrent protection devices such as solid-state power switches, conventional reclosers, fuses, and relays. These devices have the problem of being unable to determine the direction of current, despite the fact that relays have been stated as being able to do so [2].

Directional overcurrent relays are utilized for power system protection to ensure safe, reliable, and efficient operation. The relay monitors the current flow in the circuit that is being protected. When the short circuit current flow in a specific direction exceeds a preset value, A trip signal is sent to the circuit breaker by the relay [3]. These relays have been used to the design of economical alternatives for primary and backup power system protection [4]. When a fault occurs, primary relays activate and are supported by backup relays, which activate when the primary relay fails [5]; this ensures that just the defective area of the network is isolated. This may be accomplished by appropriately determining the operating time of the relays [6].

Generally, these relays have two settings: time multiplier setting (TMS) or time dial (TD) and plug setting (PS) or pickup current (IP). The operating time of each relay is determined by these parameters [7,8]. The relay coordination studies attempt to determine each relay's TMS, PS, and type of tripping characteristics. The overall operating times of the primary relays should be reduced to ensure minimal network outage. To ensure that the selectivity study is valid, the specified coordination time interval (CTI) between the primary and backup protections must be maintained [9].

For the coordination of the directional overcurrent relays, the total operational time of primary relays should be minimized as much as possible by maintaining coordination among other relays. A robust time multiplier setting is also necessary to accommodate all possible operational conditions [10]. As a result, the coordination problem can be formulated as an optimization problem with the purpose of decreasing overall total operational time of primary relays while taking into account various constraints and boundary limits [11].

## 1.2 Problem Statement

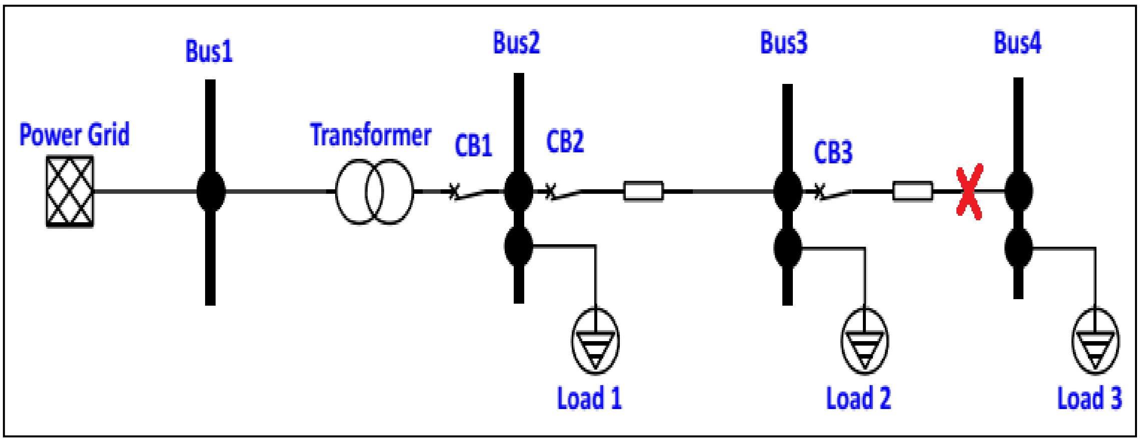
The process of modifying protection device settings such that they operate in a specific order to minimize power service disruption caused by a power system disturbance is known as coordination of protection devices [12]. When a fault occurs in the power system, the relay closest to the fault must trip first. If the closest protection relay fails to detect the fault due to a longer operating time, the backup protection relay will trip quickly to prevent the fault from propagating throughout the power system. Thus, coordination between the primary and backup relays is necessary for avoiding malfunctions.

To demonstrate the coordination problem, consider Figure 1.1, which illustrates a radial power system with a fault at point (X). CB3 will act as the primary protection, while CB2 will operate as backup protection. For this fault, CB3 must be opened, but CB2 and CB1 must remain closed. Under these conditions, only load 3 is interrupted. We may choose a longer time delay for the relay at CB2, allowing CB3 to operate first. We also choose the CB1 relay with a higher time delay than the CB2 relay, so that the CB2 relay opens first. There is an interval between the relays called coordination time interval (CTI). That is the amount of time it takes for circuit breakers to clear the fault under primary relaying after backup relaying has started operating [13]. This emphasizes protective relaying coordination, which involves selecting a proper settings for each relay so that their primary protection function is accomplished while maintaining the existing features of protective relaying, including reliability, speed, sensitivity, and selectivity [14].

To obtain the optimum settings of the directional overcurrent relays, it is possible to define the coordination problem as an optimization problem. Various techniques and methods have previously been developed to solve the problem.

**Figure 1.1**

*Radial Network*




### 1.3 Significance of Research

The significance of this research derives from the importance of integrating two optimization algorithms to solve the coordination problem. The main purpose of this study is to investigate the coordination problem of the directional overcurrent relays and to solve it by developing modified firefly algorithm, standard genetic algorithm and new hybrid optimization technique to obtain better solution.

### 1.4 Research Objectives

The objectives of this study can be summarized as follows:

1. Review the optimization algorithms utilized to solve the coordination problem.
2. Develop a modified version of the firefly algorithm to solve the coordination problem.
3. Use the standard Genetic algorithm to solve the coordination problem.
4. Solve the coordination problem by combining two metaheuristic algorithms, firefly algorithm and genetic algorithm to get better solution.
5. Accessing the performance of modified firefly algorithm, genetic algorithm and hybrid firefly genetic algorithm by implementing them to the standard IEEE 3-bus, 6-bus, 9-bus and 15-bus test networks.
6. Verify the proposed optimization techniques by comparing them to up-to-date optimization algorithms that have been utilized to solve the coordination problem.

### 1.5 Research Scope

The scope of this research will be focused on electrical protection systems and the application of optimization algorithms to solve electrical protection system problems such as the overcurrent coordination problem.

### 1.6 Overcurrent Protection in Power System

To better understand the overcurrent protection concepts, this section reviews the fundamentals of the overcurrent protection, beginning with the major principles of the protection system. After that, discusses the causes of overcurrent in power system and the need for overcurrent protection. Moreover, the various overcurrent relay types and their directionality characteristic. Finally, explains the protection coordination of the overcurrent relays.

#### 1.6.1 Protection System Concepts

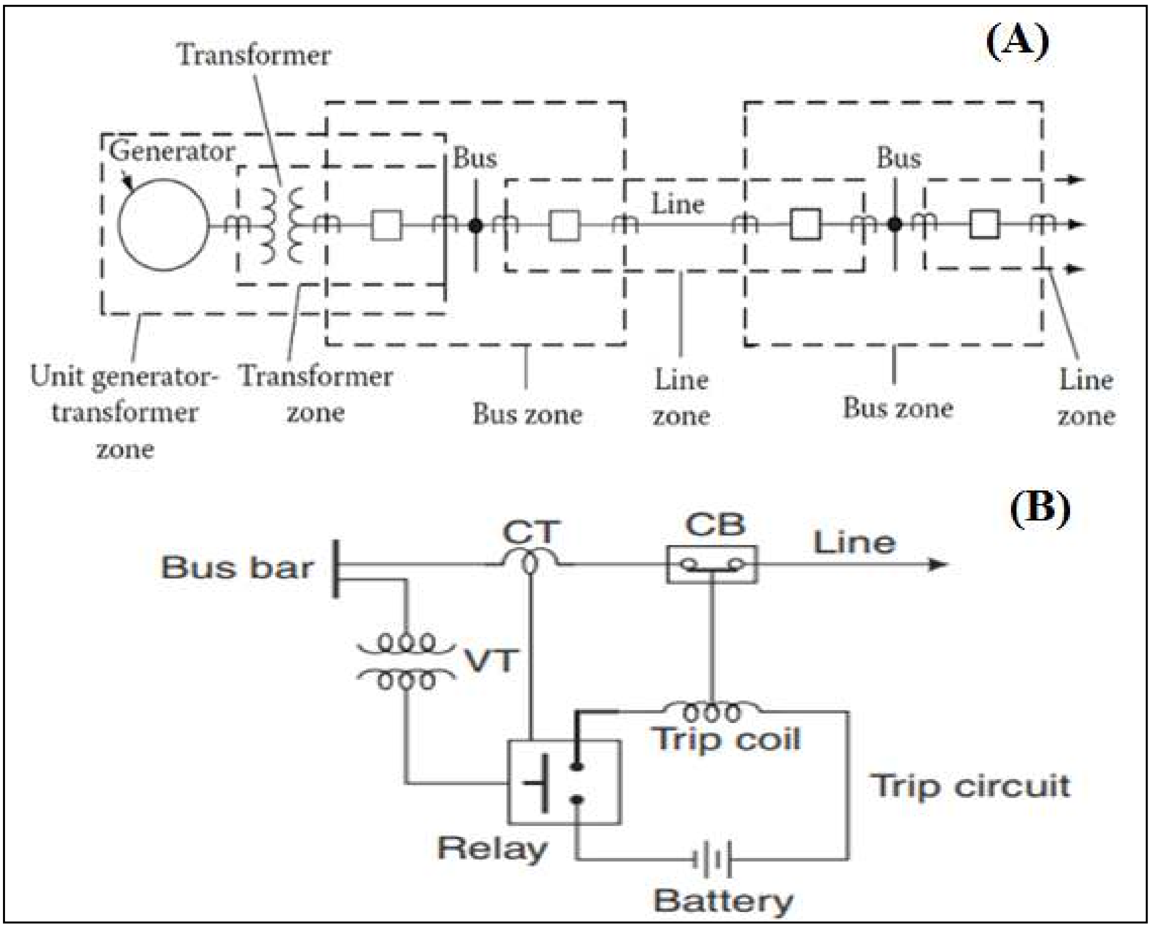
Protection system must operate properly (reliable), isolate the fault by disconnecting only the system component that is faulty (selectivity), clear the fault in the shortest amount of time, and ensure coordination at the lowest feasible cost. The general philosophy to implementing protection to power systems is to divide it into separate zones. Protection devices are chosen and assigned to protect a specific potion of the power system. The protective device is in responsibility of this section, which is referred to as the primary zone of protection [15]. These protective zones include the whole power system, protecting each part. Protection of sections that are on the boundaries of two protected zones as well as sections that may not be in either of these zones is made possible by the overlap of these zones as shown in Figure 1.2 (A) [16,17]. In the design of a protection system, the primary protection is backed up by a backup protection that must trip if the first one fails [18]. In order to allow the primary protection enough time to operate, The primary protection's operational time must be longer than the backup relay [15].

The main components of a protective system are presented in Figure 1.2 (B), which are as follows [19]:

1. Transducers: Current transformers (CT) and potential transformers (PT) provide the information necessary for fault detection at standard lower levels. Additionally, in order to protect protective relays from the high voltages of the power system, currents are typically reduced to either 5-A or 1-A and voltages are minimized to 110-V or 120-V [15,19].
2. Protection Relay: a relay whose purpose is to detect abnormal or dangerous power system circumstances or other faulty equipment conditions and to initiate the proper control circuit action [17].
3. Circuit breakers and trip circuit containing trip coil and battery: to isolate the faulty parts [15].

**Figure 1.2**

*Protection System Concepts*




Note: Subfigure (A) represents the protection zones in power system and it is adapted from [17], subfigure (B) represents the components of a protection system and it is adapted from [19].

The relay that is connected to the CT and VT activates and closes its contacts when there is a short circuit in the protected circuit, completing the trip circuit. In the trip circuit, current is being supplied by the battery. The circuit breaker's trip coil activates the operating mechanism, which powers the opening process to disconnect the defective element [19].

### 1.6.2 Overcurrent Protection

Overcurrent may result from either abnormal system circumstances, such overload and short circuits, or from normal system conditions, including transformer inrush current and motor starting. Protective relays are included in power systems so that switching equipment can only activate in response to abnormal system circumstances [15].

#### 1.6.2.1 Overcurrent Relays

The least expensive and easiest type of protection is provided by overcurrent relays [19]. Any power system element that has a fault will nearly always experience a short circuit current that is larger than the pre-fault load current. Using the current magnitude as a fault indicator is a very basic and efficient relaying principle [20]. Overcurrent relays respond to the amount of the input current and activate when the input current rises above the specified value. The relay closes its trip contacts and energizes the circuit breaker trip coils when this threshold is reached [16].

**1. Overcurrent Relays Types**

Based on their operating time characteristics, overcurrent relays can be divided into the following categories:

a. Instantaneous overcurrent relay (definite current): When the current reaches a specific level, the relay functions instantaneously as shown in Figure 1.4 (A). The only operating condition is current magnitude, and it operates in 0.1 seconds or less [16].

b. Definite time overcurrent relay: As illustrated in Figure 1.3 (B), after a specified current level is reached, these relays have an operating time that is unaffected by the current magnitude. This type of relay has two settings: a time-dial setting to select the actual time the relay functions, and a current setting (also called as a pickup, plug, or tap setting) to choose the current value at which the relay will operate [15].

c. Inverse time overcurrent relay: An inverse-time overcurrent relay activates when the current is greater than its pick-up value. The operating time is determined by the operating current's magnitude. As the current rises, the operating time reduces. The inverse time-current characteristic of these types of relays is shown in Figure 1.3 (C) [19].
d. Inverse definite minimum time (IDMT) overcurrent relay: The IDMT overcurrent relay combines the characteristics of definite current and inverse time for discrimination. Figure 1.3 (D) shows the curve representing its operating characteristic [16]. In general, if the plug setting multiplier value is less than 10, an inverse-time characteristic is obtained. The characteristic tends to become a straight line, or toward the definite time characteristic, for plug setting multiplier values between 10 and 20. Relays for IDMT are frequently used to protect distribution lines [19].

The further classes listed below are based primarily on the inverse characteristics of overcurrent relays shown in Table 1.1 and are defined by IEC 60255-3 and IEEE C37.112-1996 standards [21].

Figure 1.4 shows the overcurrent relay's standard tripping characteristics curves, Figure 1.4 (A) depicts the IEC standard characteristics, whereas Figure 1.4 (B) represents the IEEE standard characteristics (B).

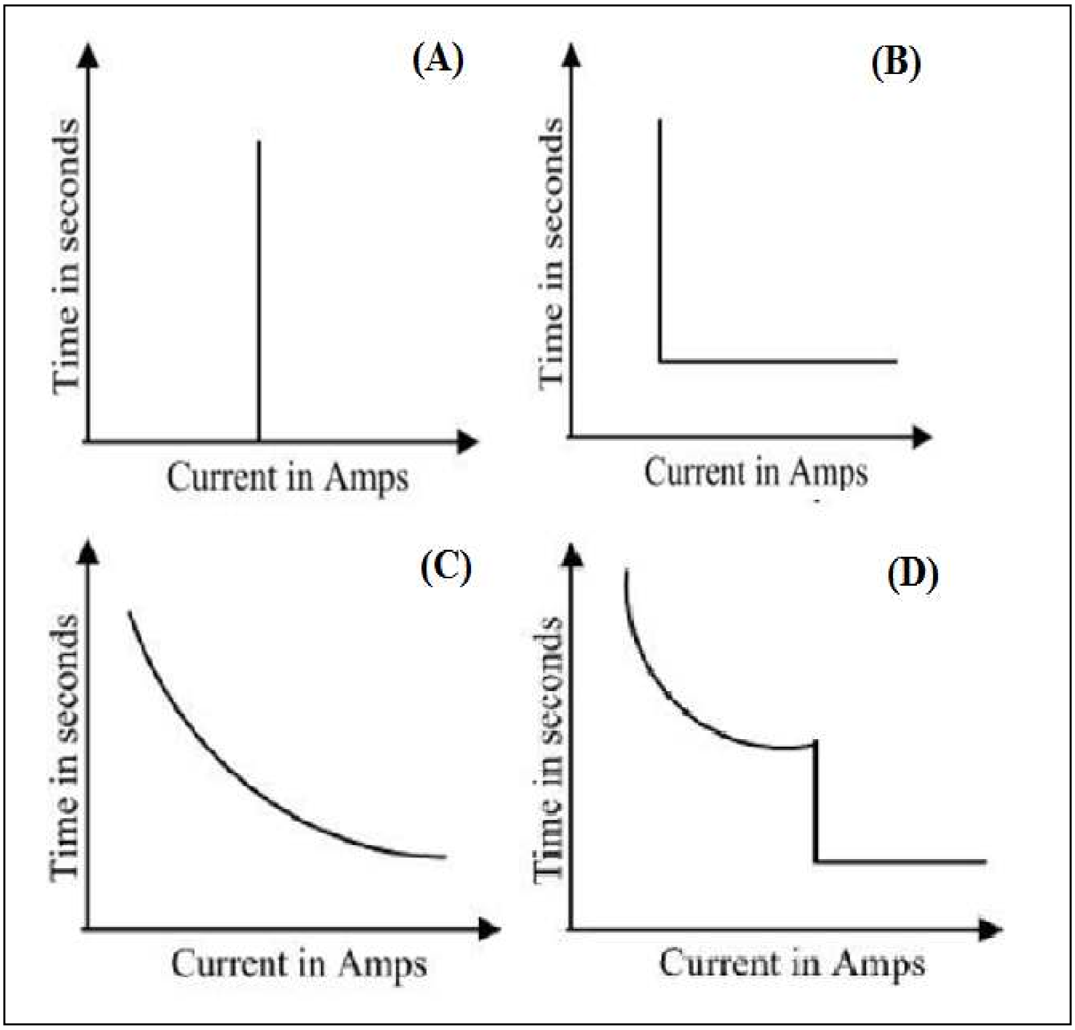
**Table 1.1**

*Standard inverse characteristics of overcurrent relays defined by IEC and IEEE.*

| **Standard characteristics** | | | |
|---|---|---|---|
| **IEC** | | **IEEE** | |
| IEC short time inverse | STI | Moderately inverse | MI |
| IEC normal/standard inverse | SI | Very inverse | VI |
| IEC very inverse | VI | Extremely inverse | EI |
| IEC extremely inverse | EI | Inverse | I |
| IEC long-time inverse | LTI | Short Inverse | SI |
| | | Long Inverse | LI |

**Figure 1.3**

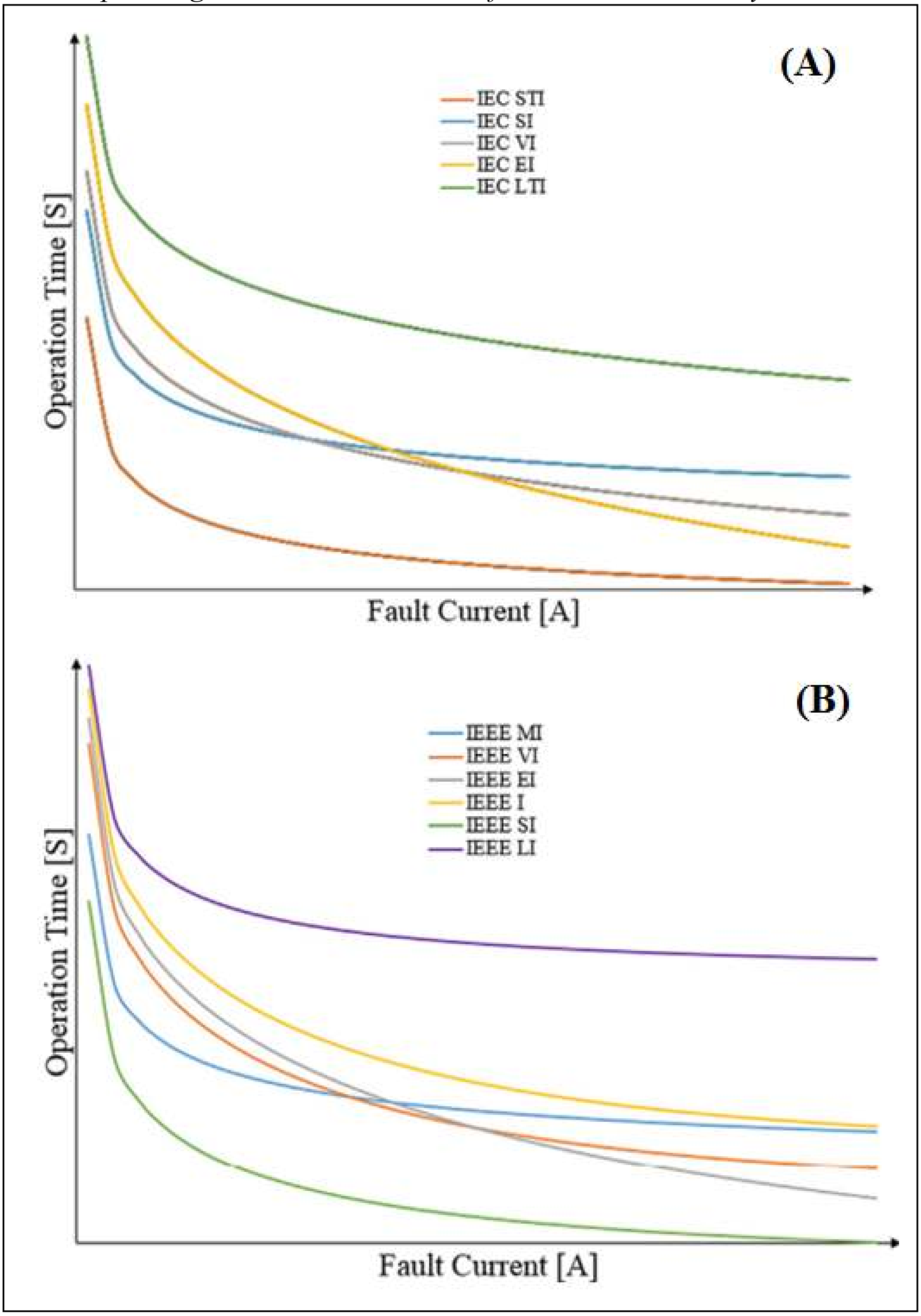
*Overcurrent relay operating time characteristics.*




Note: Adapted from [16]. Subfigure (A) represents definite current operating characteristic of the overcurrent relay, subfigure (B) represents definite time operating characteristic of the overcurrent relay, subfigure (C) represents inverse time operating characteristic of the overcurrent relay and subfigure (D) represents IDMT operating characteristic of the overcurrent relay.

**Figure 1.4**

*Standard operating characteristic curves of the overcurrent relay*




Note: Adapted from [21]. Subfigure (A) represents the IEC standard operating characteristic curves of the overcurrent relay and Subfigure (B) represents the IEEE standard operating characteristic.

**2. Operating Time of Overcurrent Relays**

IEC 60255 and IEEE C37.112 specify the overcurrent relay's operational time in Equation (2.1) as follows:

$$t = \frac{T_D \, \alpha}{(\frac{I_{SC}}{I_{PU}})^{\beta} - 1} + C \quad (2.1)$$

Where:

t: the relay operating time in seconds
$T_D$: the time dial, or time multiplier setting
Isc: the fault current level in secondary amperes
$I_{PU}$: the tap or pickup current setting
C: the constant
α: the slope constant
β: the slope constant

The slope of the relay characteristics is specified by α and β. In Table A.1, the values of α, β, and C for several standard overcurrent relay types manufactured in accordance to IEC and IEEE Standards are given [22].

**3. Current (plug) Pickup Setting**

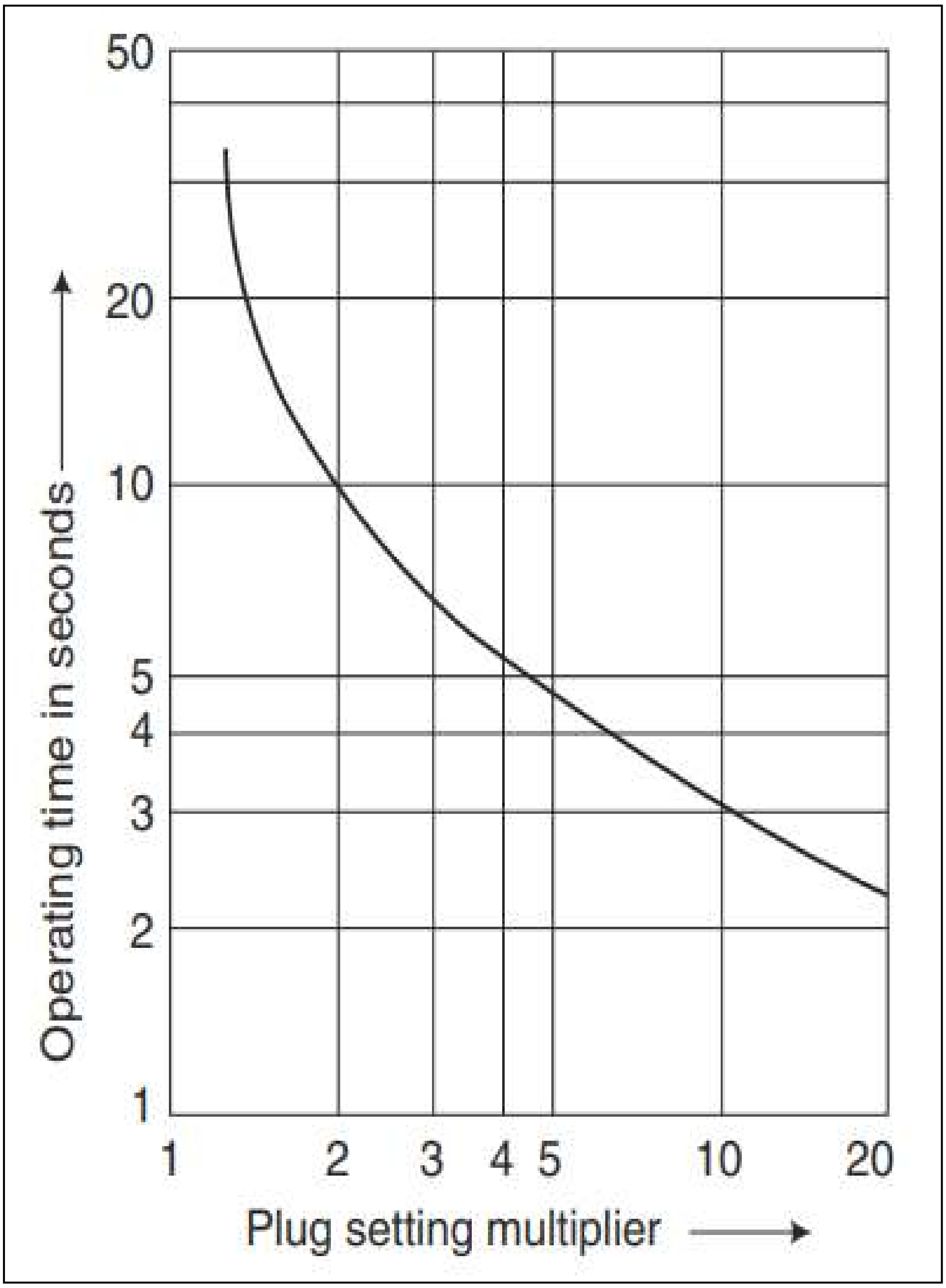
The level of current at which the relays will operate is determined by this setting [23]. The plug setting multiplier (PSM) measures the actual RMS current passing through the relay as a multiple of the setting current. However, PSM can be expressed as:

$$PSM = \frac{Secondary\ Current}{Relay\ current\ setting}$$
$$= \frac{Primary\ Current\ during\ falut}{Relay\ current\ setting * CT\ ratio} \quad (2.2)$$

A time-current characteristic with PSM on the X-axis is shown in Figure 1.5. Typically, a log/log graph is used to plot the curve. The operating time for various relay settings can only be specified by this curve [19].

**Figure 1.5**

*Standard I.D.M.T. characteristics*




Note: Adapted from [19].

The following expression illustrates how to determine the pickup setting for phase relays by allowing an overload margin exceeding the nominal current [15]:

$$Pickup\ setting = \frac{k_{ld} * I_{nom}}{CTR} \tag{2.3}$$

Where:

$K_{ld}$: overload factor that based on the element being protected.
$I_{nom}$: nominal rated current.
CTR: current transformer ratio.

When choosing the pickup setting for earth-fault relays, the maximum unbalance that could possibly exist in the system under normal operating conditions is taken into consideration. 20% is a typical imbalance allowance, thus the expression in (2.3) becomes [22]:

$$Pickup\ setting = \frac{0.2 * I_{nom}}{CTR} \tag{2.4}$$

**4. Time Setting**

Time dial setting modifies the time delay before the relay functions whenever the short circuit current equals or exceeds the relay current setting. In electromechanical relays, where the time delay is frequently obtained by adjusting the physical distance between the moving and stationary contacts, a lower time dial value results in shorter operating times. The time dial setting is also known as the time multiplier setting (TMS) [22]. There are ten steps in which time can be set. For these time-setting steps, the term TMS is used.

### 1.6.2.2 Directional Overcurrent Relay

Nowadays, with the expansion of the electric grid and the increasing complexity of the power system, the protective system has become an essential part of the power system. Directional type overcurrent relays are employed for bidirectional power flow feeders. [24]. Utilizing the directionality function, which operates in the forward or reverse value depending on the current and voltage values and the polarization angle, can prevent incorrect operation. The phase shift of the current angle relative to the voltage angle determines the directionality torque function, therefore the directional protection relay has to be fed from both the secondary sides of the line current and voltage transformers [25].

### 1.6.3 Protection Coordination of Overcurrent Relays

The primary relay must function initially to protect its own zone through an appropriate time interval, with all the fault-free parts remaining in operation. This is the basis for the coordination of overcurrent protection relays [15]. If the primary relay fails to isolate a fault within its own zone, the backup relay should eventually be able to do so by isolating the fault but with a larger area of the faulted zone, which includes part of the non-faulted zone [11]. The settings for the relays are modified such that the primary relay nearest to the defect responds quickly to operation, followed by all of the backup relays [26]. The different types of coordination are time-based coordination, current-based coordination and logic coordination.

#### 1.6.3.1 Coordination Time Interval

Time-current coordination of the overcurrent relays is required to ensure selectivity and isolate only the faulty part. With a specific coordination time interval (CTI), a downstream device must operate more rapidly than the upstream device. In order for series-connected protection devices to operate sequentially, a minimum CTI must be maintained throughout the operational range. Typically, a CTI on the order of 0.20-0.50 seconds should be utilized between two sequential time/current characteristics. Due to one or more of the following, this value prevents selectivity from being lost [18]:

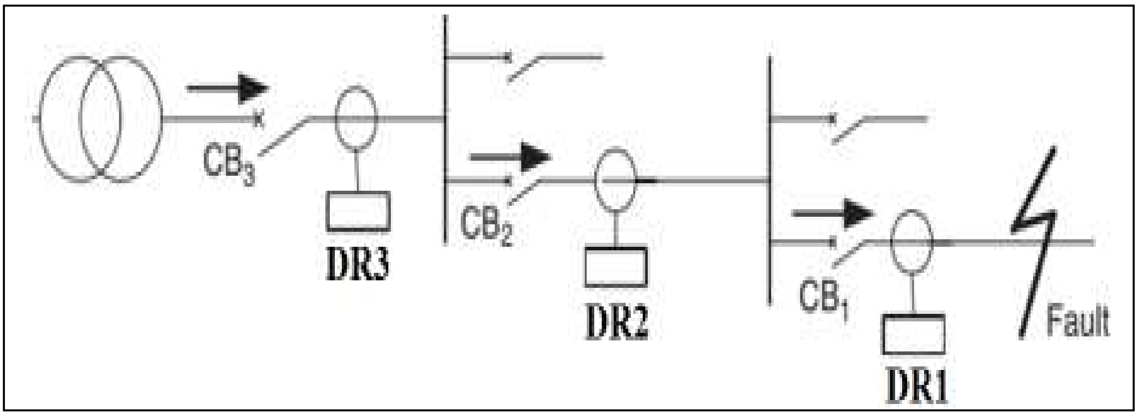
- Circuit breaker interrupting time.
- Relay overrun time after the fault has been cleared.
- A safety factor that takes CT saturation and setting errors into consideration [22].

#### 1.6.3.2 Time-Based Coordination

During fault conditions, accurate discrimination could be achieved by utilizing relays configured to operate at different time delays. It is obvious that the timing differences between the relays connected to adjacent sections could be sufficiently large to allow the relevant circuit-breaker to open and isolate the fault on its section before the relay connected to the adjacent section closer to the source could start opening its circuit-breaker [27]. As depicted in Figure 1.6, the fault is detected by relays DR1, DR2 and DR3. The DR1 functions faster than DR2, which in turn functions faster than DR3. Protection units DR2 and DR3 return to the standby state once the CB1 is tripped and the problem is resolved. The difference in operating time $\Delta t$ between two subsequent protection relays is CTI. This coordination system benefits from being simple and providing its own backup; for instance, if DR1 fails, DR2 is activated after $\Delta t$ [15]. This type of coordination, meanwhile, would fall short in networks where the fault current varies based on where the fault lies [16].

**Figure 1.6**

*Radial Power System Protection*




Note: Adapted from [15].

According to the protection characteristics, three different time delay types are used: definite time, inverse-time, and combined inverse-time and instantaneous protection systems [15].

- Definite-time protection: as seen by the protection tripping curves shown in Figure B.1, the time delay is constant and independent of the current [15]. For this type of protection, it is recognized that relays utilized close to the sources in networks with different sections connected in series may have unacceptable high operation times for faults in the sections they protect since such faults could be at current levels which can only be permitted to exist for short durations [27].
- Inverse-time protection: As illustrated in Figure B.2, inverse curves operate faster at greater fault currents and slower at lower fault currents [23]. For a fault at the end of the section closer to the power source, a relay whose delay is inversely proportional to the current would trip faster in this case. In the event where the selection intervals are the same, inverse time relay can offer faster clearing times than definite time relay [28].

- Combined inverse-time and instantaneous protection: It operates on the same IDMT concept and trips instantly at the highest downstream short circuit current. This type of tripping curve is shown in Figure B.3 [15].

#### 1.6.3.3 Current-Based Coordination

In circuits where there will be a significant variation in the ratio of fault current to rated current in different parts of a network, current-based coordination can be employed to achieve proper discrimination. As illustrated in Figure B.4 [27], the operating time is maintained constant for all relays employed to protect various feeder segments. This coordination is based on the concept that discrimination is made possible by decreasing the current setting as one moves from the load to the power source. Thus, the relay nearest to the fault will always trip first [16]. The benefit of this system over the time coordination technique is that it requires less operating time when close to the power source [19]. This approach has the drawback that the fault current does not necessarily change with the location. As a result, accurate relay discrimination is not achievable [16].

#### 1.6.3.4 Time-Current Based Coordination

The most common method of coordination is the time-current coordination scheme [16]. They combine the characteristics of time-and current grading. IDMT relays are employed in this scheme. Time and current settings are available for IDMT relays. According to the short circuit current level of the specific zone that has to be protected, the relay's current setting is set. The relays are configured to pick up gradually at greater current levels, in the direction of the source. Furthermore, time setting is also described in progressively higher order away from the source [19].

## 1.7 Optimization Techniques Applied For Overcurrent Relays Coordination Problem

This section provides a survey of the conventional optimization techniques, heuristic techniques, and hybrid optimization techniques that have been used for solving the coordination problem.

### 1.7.1 Optimization Techniques

For solving the coordination problem, different techniques have been developed. These techniques can be divided into four categories: dual setting protection schemes, new constraints for optimal coordination, non-standard characteristics, and optimization techniques. The optimization algorithms applied for the coordination problem are presented in this section. Relay coordination is characterized as an optimization problem that can be resolved by employing optimization techniques that fall under the following categories represented in Figure C.1.

#### 1.7.1.1 Mathematical Based Optimization Techniques

Several electrical engineering and relay coordination problems were solved using various optimization techniques. Conventional techniques have the idea that fault studies, system emergencies, and abnormal conditions should be predetermined [5,24,29]. The conventional techniques involve trial and error, and topological techniques [30]. Power system engineers have previously used a trial-and-error methodology to determine the best relay settings. However, the rate of convergence for this methodology is slow due to the several iterations required to find a suitable relay setting, and it may not always produce acceptable relay settings [8,12,30–37]. Breakpoint technique was applied to solve this problem [38]. The break points are determined using topological methods based on graph theory and functional dependency to decrease the number of iteration needed for relay coordination process [5,24,37,39,40]. The solutions obtained from these techniques are among the best of all feasible solutions, but they are not optimal. In other words, the relays' TMS are quite large [24,37,40–42].

The coordination problem in such complex networks was solved using a computer with a graphical user interface. In [43], the coordination problem of the inverse definite minimum time over current relays has been solved using Computer Aided Protection Engineering (CAPE). The graphical user interface of CAPE is useful since it enables protection engineers to make any required adjustments, revisions, or even upgrades to the current setting to ensure good coordination with the network system. Matlab Graphical User Interface (GUI) has been implemented to solve the inverse-time and instantaneous overcurrent relays coordination problems as presented in [44]. The GUI provides curves of various standardizations that can generate coordination charts by varying the slopes of inverse-time curves and the adjustment parameters of instantaneous and timed overcurrent functions.

Deterministic methods, which are characterized as mathematically-based optimization techniques which are utilized extensively to solve overcurrent relays coordination problems, are classified as shown in Figure C.2 [11,29].

Depending on the nature of settings in the coordination problem, the protective relay coordination problem typically modelled as either an LP, NLP, MILP or MINLP problem [44]. LP has some benefits such as fast computational time and simplicity to resolve, but it needs expertise to set the initial guess for pickup current settings and may get stuck in local minima [34,44]. The Big-M method, in which the PS are considered to be known and fixed, has been suggested in [45] to obtain the optimum value of time multiplier settings of directional overcurrent relays. Due to the non-linear nature of the relay configuration, it is extremely inefficient and complex [29,46]. The directional overcurrent relays problem was stated as a NLP problem to overcome the challenges by designating TMS and PS as decision variables [2]. The optimum relay settings have been obtained applying the non-linear programming Rosenbrock-Hillclimb technique in [47]. Both the decision variables are calculated and optimized in MINLP [48]. As a result of the coordination problem's non-linearity and non-convexity, NLP and MINLP techniques are susceptible to become trapped in local minima. Therefore, a formulation based on MILP has been suggested for the coordination problem in [49] to overcome these problems by taking into account the PS as a discrete optimization variable and the TMS as a continuous optimization variable. The problem has been solved using the branch and bound approach. Therefore, at each branch, the proposed formulation converts the nonlinear and nonconvex coordination problem into a linear and convex problem. This matter assures convergence to global optimal settings and makes the problem easier to solve.

These methods' main drawback is that they are highly dimensional, and in order to solve the coordination problem, they require a lot of computational time and computer memory [29]. The problem of a minimum solution plagues conventional methods, especially in the case of complex systems, despite the fact that they provide a considerable contribution to the problem's solution. Convergence is also difficult to achieve [11]. Table 1.2 compares between these mathematical algorithms.

Authors in [39] suggested analytical method to determine the optimal directional overcurrent relays settings. The suggested numerical technique converges to the global optimal values, which are independent by the relay setting order and initial values. To accurately determine the critical fault point to coordinate overcurrent relays, authors in [53] presented an analytical method for calculating the network's impedance matrix in a fault condition. Relay coordination problems for mid line faults were successfully optimized using a gradient search-based method in [54]. These techniques often use a lot of iterations to calculate the relay settings and fall short of determining the optimal setting of the relay for an interconnected power network. Nevertheless, for radial systems, analytical methods are very effective [48,55,56].

**Table 1.2**

*Comparison between mathematically-based optimization methods.*

| Reference | Mathematical algorithm | Remarks |
|---|---|---|
| [45,50,51] | LP | The only design variable considered is TMS, whereas PS values are fixed between allowable overload and minimum short circuit currents. As a result, each relay's operational time is computed as a linear function of time dial setting. |
| [2] | NLP | Both the TMS and the PS are regarded as decision factors and are regarded to be continuous variables. |
| [52] | MILP | The PS values are defined as discrete variables and the TMS as continuous variables. |
| [48] | MINLP | TMS values are considered as continuous variables and PS values are regarded to be integer variables. |

#### 1.7.1.2 Meta-Heuristic Optimization Techniques

Researchers and scholars have recently used various heuristic, metaheuristic, and evolutionary algorithms to obtain solutions to electrical engineering problems, such as the optimum settings of overcurrent relays coordination [33,57–59]. Artificial intelligence has recently attracted a lot of interest for its ability to optimize directional overcurrent relays settings [24,48,60,61]. They populate a number of solutions to start the optimization process rather of starting with just one, as in conventional ones. Additionally, for complex tasks, their gradient independence can increase their flexibility [55]. The protection system's speed can be improved by choosing the appropriate characteristics for modern directional overcurrent relays, though. Artificial intelligence methods that take into account the operation characteristics of the relay as an optimization parameter together with time multiplier settings and plug settings can help achieve this [62]. The operator carefully examines the power system limits before selecting the relay settings in the conventional optimization of relay coordination. The maximum fault current, load current, fault clearing time, current transformers ratios, and other constraints must be checked in order to yield adaptive curves. These checks are not supported by many commercial computer software products. Relay coordination has been solved by artificial intelligence in terms of a constrained objective function [63].

Different metaheuristic algorithms has been applied to optimize the coordination problem, such as Genetic Algorithm (GA) [64], Particle Swarm Optimization (PSO) [65], Seeker Algorithm (SE) [48], Crow Search Algorithm (CrSA) [61], Firefly Algorithm (FA) [66], Honey Bee Algorithm (HBA) [67], Differential Evolution (DE) algorithm [32], Harmony Search Algorithm (HSA) [42], Artificial Bee Colony (ABC) [68], Cuckoo Search Algorithm (CSA) [69], Whale Optimization Algorithm (WOA) [70], Water Cycle algorithm (WCA) [71], Teaching Learning Based Optimization (TLBO) algorithm [72], Harris Hawk Optimization (HHO) [73], Grey Wolf Optimizer (GWO) [74], Improved Group Search Optimization (IGSO) [75], Sine Cosine Algorithm (SCA) [76], Shuffled Frog Leaping Algorithm (SFLA) [77], Symbiotic Organism Search technique (SSO) [78], JAYA algorithm [79], and Seagull Optimization Algorithm (SOA) [31].

#### 1.7.1.3 Hybrid Optimization Techniques

There are significant drawbacks to artificial intelligence based optimization techniques, including premature convergence, higher computation time, initial solution sensitivity, and significant speed differences. Due to the fact that no single algorithm is capable of solving all possible varieties of optimization problems, there is always a chance of convergence to local minima [11,55,80,81]. Hybrid optimization techniques, which integrate different optimization algorithms, are employed to overcome these problems. They make it possible for each approach to work more effectively and accurately than it could on its own [11,55,80].

GA has the shortcoming of sometimes converging to values that are not optimal, whereas the drawback of NLP approaches is that they tend to converge to local optimal settings when the initial choice is closer to the local optimum. GA is a multipoint search technique that explores a large solution space, in contrast to conventional single point search techniques. In [82], the authors effectively combined the features of GA with NLP to find the optimal relays settings. The authors in [83] suggested a technique for adaptive coordination of overcurrent relays considering the topological changes of the radial and meshed networks using the existing relay setting groups. A hybrid GA and LP technique has been employed to solve the issue, where the GA categorizes the scenarios of network topology changes into a limited number of setting groups in a near-optimal manner, and the LP method optimally coordinates the overcurrent relays within the setting groups. In [84], the coordination problem has been solved using hybrid optimization method that combined the integer coded genetic algorithm ICGA and NLP techniques. The authors in [85] developed a method for optimizing overcurrent relay coordination using computational intelligence approaches applied to adaptive protection in the context of DG. The developed hybrid algorithm utilizes fuzzy logic to control the current settings and GA to determine the relay's TDS and curves.

The convergence rate of PSO is slow, and optimization problems with constraints cannot be solved efficiently. In [86], hybrid PSO has been utilized to efficiently coordinate DOCRs. The optimal IP setting is determined using PSO, and the TDS of each relay is determined using the LP approach. In [87], the same technique used in [86] was successfully applied to coordinate DOCRs in a microgrid system. The authors in [88] and [89] proposed a hybridization of Nelder-Mead simplex search approach with PSO to solve the coordination problem. Nelder-Mead simplex search with a faster reach to the optimum settings and PSO to achieve the globally optimum solution, as well as combining the two algorithms and the gradient-based repair approaches allows for the discovery of feasible optimal solutions that satisfy the constraint conditions. In addition to [88] and [89], the various network topologies have been successfully included in [90]. In [91], an efficient variant of the PSO algorithm known as Time Varying Acceleration Coefficient (PSO-TVAC) was developed to determine the optimal settings for directional overcurrent relays. TVAC's goal is to improve the global search and encourage particles to converge on the global optima at the end of the search. A hybridization between particle swarm optimization and differential evolution technique

(PSO-DE) has been performed in [92]. This technique yields the most globally optimal solution at a faster convergence rate. The coordination problem in [80] and [60] was successfully solved using a hybridized version of particle swarm optimization (HPSO). In order to avoid getting stuck in local optima and successfully search for a global optimal solution, the hybridization was accomplished by incorporating simulated annealing (SA) into the original PSO.

In [93], hybrid ABC with LP has been proposed to improve the conventional ABC algorithm performance. These decreased the search space, resulting in time consuming and computational efficiency in determining the optimal solutions. In [94], an effective combination of two optimization techniques, SFL and LP, has been proposed for the coordination problem. In [8], a new population-based evolutionary algorithm called biogeography-based optimization (BBO) has been proposed as an optimization method for optimal relay coordination problem. In addition, to improve convergence speed and accuracy, a hybrid BBO with LP has been developed, and the hybridization demonstrated that the needed number of populations and generations has been greatly reduced with better optimized fitness and required lower CPU time.

In [33], the authors performed a hybridized version of the WOA by establishing the SA into the WOA algorithm to enhance the optimal solution obtained after each iteration and improve exploitation by searching the most promising regions identified by the WOA algorithm, which results in a globally optimal solution. To gain the global search capability of HHO and the precise local search capability of sequential quadratic programming (SQP), the authors in [11] presented a hybrid HHO-SQP to give a globally optimum solution. Since the Moth-Flame Optimization (MFO) performs effectively in the exploitation phase. The water cycle algorithm's performance has been enhanced by the hybrid water cycle and moth flame (WCMF) algorithm, which has been developed in [95]. The Levy flight function was included to investigate randomization of the current hybrid model, which increased its performance. An efficient combination of gradient-based optimizer (GBO) and memory-based linear population size reduction technique of Success-History-based Adaptive Differential Evolution (LSHADE) algorithm has been presented in [55] to develop novel hybrid optimization model called GB-LSHADE. The GBO was used to explore potential regions of search space, while the LSHADE algorithm was used as a local search scheme to improve the diversity of solutions and avoid premature convergence.

In [26], a new optimization strategy named FPSOGSA has been proposed by including the concept of fractional calculus inside the mathematical model of canonical PSO and integrating it with gravitational search algorithm (GSA) to improve the optimizer characteristics by enhancing the convergence rate and preventing premature convergence. Optimal coordination of directional overcurrent relays in modern distribution systems with a high concentration of DG successfully proposed in [96] using hybrid harmony search and simulated annealing (HS-SA) technique.

The optimal solution for the coordination problem in a microgrid under different modes has been solved using hybrid programming of interval linear programming (ILP) and DE in [46]. By presenting short circuit current magnitudes as intervals and formulating a linear objective function, the complexity of overcurrent relays' optimal coordination in a microgrid was successfully reduced. In [2], a hybrid FA and LP (FA-LP) has been combined to improve the solution quality and convergence rate of the FA, resulting in a technique that relaxes the search space by linearizing the directional overcurrent relays coordination problem and avoids it from being trapped at the local optima.

The recently developed FA, based on the flashing behavior of fireflies, is a nature-inspired optimization algorithm utilized for evaluating the complicated and highly nonlinear constraints [35]. In a highly efficient way, FA can simultaneously find the global and all local optima. It doesn't need a suitable initial guess to start its iteration process because of the fast convergence speed of firefly and the high probability of obtaining the global optimisation solution. Another benefit of FA is that each firefly will operate practically independently, making it especially well-suited for parallel implementation. In parallel implementations, there are very few interactions between the various subregions [97]. Although it has many drawbacks similar to other inspired algorithms. For example, in the case of high dimensions, the algorithm would easily reach the local minimum value, which lowers the performance of the solution by reducing its attractiveness [98].

In this research, a modified firefly algorithm is implemented to solve the coordination problem. Compared to standard firefly algorithm, the attractiveness and randomized movements parameters are controlled to obtain a global solution and produce a good convergence rate. The study then proposed the combination of genetic algorithm with the modified firefly algorithm as a new generation which can obtain better solutions and make a balance between global and local search. Additionally, it can get rid of trapping into various local optimums. Besides, to the best of the author' knowledge, the hybrid firefly-genetic algorithm hasn’t yet been optimized the directional overcurrent relay coordination problem.

## 1.8 Thesis Outline

This thesis is organized in four chapters and three appendices. The first chapter of this study begins with an introduction that includes an overview of the research, identification of the problem statement, description of the significance and scope of the research, review of overcurrent protection in the power system, and review of the optimization techniques applied to optimize the coordination problem. Chapter 2 describes the methodology used in this study; it consists of the formulation of the optimization problem, the description of techniques used to solve the coordination problem, and a description of the testing systems used in simulation. Chapter 3 presents the results achieved from the proposed algorithms for each test system with discussion. The results include the optimized relay settings, the minimum total operating time obtained by the proposed methods in comparison to the literature, the overall net gain and the percentage performance in the operating time obtained by the suggested methods and finally presents the objective function evaluation number results for the GA and the hybrid algorithm to illustrate the efficacy of the developed hybrid algorithm. Chapter 4 concludes the study with some future research directions. Appendix A includes the IEC and IEEE standards Constants for Overcurrent Relays. Appendix B presents the time-delay coordination characteristics for different types of overcurrent relays. Figures related to the optimization algorithms used in this study are shown in Appendix C. In Appendix D, figures related to the proposed method applied in this study are presented. Appendix E includes the relay pairs and related parameters for the IEEE 3-bus, 6-bus, 9-bus and 15-bus networks. The simulation results for the IEEE 6-bus, 9-bus, and 15-bus networks are provided in Appendix F. The Matlab codes of the proposed methods that used to solve the coordination problem of the IEEE 3-bus network are provided in Appendix G.

# Chapter Two
# Methodology

## 2.1 Introduction

Figure D.1 illustrates the general steps that will be taken for the optimum coordination of the directional overcurrent relays [99].

The first step is to collect all the necessary data regarding the given network. The necessary data are shown in Figure D.2. The second step involves utilizing ETAP software to conduct a load flow analysis to determine the maximum load current. Then all of the relay pairs are identified since coordinating relays imply that selectivity among relay groups is carried out appropriately and sequentially. If any relay malfunctions or exceeds the assigned chance, one or a set of backup relays should activate immediately. Each of these backup relays will also function as the primary relay for a different set of relays. Thus, identifying the P/B relay pairs of all relays is a very essential step for solving the coordination problem. An effective protection design should be able to detect both the largest overload current and the smallest severe faults, which are reflected in PS's permissible limits. Therefore, it is necessary to conduct a short-circuit analysis on the given network before starting the process of optimal relay coordination. The analysis of the near-end three-phase short-circuit is applied. The minimum and maximum short circuit currents were found using ETAP software. Since this study is a comparative study, all the results of the previous stages are obtained from previous works. The last stage, which applies the optimization method to determine the optimum relay settings, can then be initiated. The optimization algorithms are coded using MATLAB software.

## 2.2 Problem Formulation

The coordination of directional overcurrent relays is a complex, non-convex optimization problem that should be solved while taking a variety of different linear and nonlinear inequality constraints into consideration. Formulation of the directional overcurrent relays coordination problem can be divided as follows:

- Objective function,
- Relay settings constraints, and
- Coordination constraints.

### 2.2.1 Objective Function

In this study, minimizing the total operating times of all main relays in the system is the purpose of the problems for directional overcurrent relays. The objective function is presented by Equation (4.1);

$$\mathrm{OF} = \min \sum_{i=1}^{n} t_i \qquad (4.1)$$

Where n is the total number of primary relays (i) in the network and t is the primary relay's operating time.

To fairly compare the effectiveness of various algorithms presented in the literature, the IEC standard inverse (IECSI) characteristic is applied in this study. Refer to Table 2, the equation (2.1) will be reformulated as follows considering the European relays are used:

$$t = \frac{0.14 * TMS}{\left(\frac{I_{SC}}{PS}\right)^{0.02} - 1} \qquad (4.2)$$

### 2.2.2 Relay Settings Constraints

The objective function minimization in equation (4.1) is bound by several sets of constraints. The first set of constraints relates to the setting of the relay. It includes the upper and lower limits of current settings (IP) and time multiplier settings (TMS), which are defined in equations (4.3) and (4.4).

$$IP_i^{min} \leq IP_i \leq IP_i^{max};\ \forall i \in N \qquad (4.3)$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max};\ \forall i \in N \qquad (4.4)$$

Where, $TMS^{min}$ and $TMS^{max}$ are the minimum and maximum limits of TMS which are generally set to 0.025 and 1.1-sec [61], respectively. $I_P^{min}$ *and* $I_P^{max}$ are the minimum and maximum limits of IP. The limits of $IP$ are taken as follows:

$$k_{ld} * I_{nom} < IP < \frac{2}{3} I_{f,min} \qquad (4.5)$$

Where, $\boldsymbol{k_{ld}}$ is the overload factor and set to 1.25.

Two factors determine plug setting (PS); the first is the short circuit current, and the second is the maximum load current. PS is mathematically bounded as follows:

$$PS_i^{min} \leq PS_i \leq PS_i^{max} \tag{4.6}$$

The range of PS is graphically described in Figure D.3. Where, $PS_i^{max}$ and $PS_i^{min}$ are the maximum and minimum limits of $PS_i$ such that [26]:

$$PS_i^{max} = \frac{2 * I_{f,min}}{3 * CTR} \tag{4.7}$$

$$PS_i^{min} = \frac{k_{ld} * I_{nom}}{CTR} \tag{4.8}$$

As shown in equation (4.9), the $\boldsymbol{t_{min}}$ and $\boldsymbol{t_{max}}$ represent the time bound for the minimum and maximum operational time of the relay, The standard values for $t_{min}$ and $t_{max}$ are 0.1 and 1.1-sec, respectively [78]. Where the critical clearing time determines the maximum time and the minimum time is based on the manufacture of the relay [11].

$$t_{min} < t_i < t_{max} \tag{4.9}$$

### 2.2.3 Coordination Constraints

The coordination constraints serve to ensure that both the primary and backup relays function effectively and prevent any occurrences of unnecessary or uncoordinated relay trips. In order to ensure correct coordination, the back-up relay's operational time must exceed that of the primary relay by the pre-defined CTI shown in equation (4.10).

$$t_{backup} - t_{primary} \geq CTI_{min} \tag{4.10}$$

Where, $t_{backup}$ and $t_{primary}$ represent the operational time of the backup and primary relays, respectively. $CTI_{min}$ is the minimum coordination time interval, and is typically set at 0.20 seconds for reliable relay operation as mentioned previously. Here,

$$t_{i,k}^{back} = \frac{0.14 * TMS^b}{\left(\frac{I_{sc}^b}{PS^b}\right)^{0.02} - 1} \quad (4.11)$$

$$t_{i,k}^{pri} = \frac{0.14 * TMS^P}{\left(\frac{I_{sc}^P}{PS^P}\right)^{0.02} - 1} \quad (4.12)$$

When directional overcurrent relays are utilized, they won't need to coordinate with the relays behind them because they will work if the fault current flows in the direction that is intended for tripping [26].

## 2.3 Standard Firefly Algorithm

Firefly algorithm (FA) is a nature-inspired optimization algorithm applied for solving the complex and highly nonlinear constrained problems [35]. The FA was proposed by Xin She Yang in late 2007 and 2008 who was inspired by the movement of fireflies at Cambridge University [100]. This algorithm was developed using three idealized rules. First, all Fireflies are unisex making it possible for them to attract one another regardless of their gender. Second, the brightness and attractiveness are inversely correlated, and as the distance between them increases, both decrease. Finally, the brightness of each firefly is affected by the objective function's value [97]. Figure D.4 shows the arrangement of fireflies [35]. Based on these three principles, the fundamental procedures of the FA can be summarized into the pseudo code shown in Figure D.5.

In minimization problems, the firefly with larger light intensity has lesser objective function. Equations (4.13) and (4.14) provide mathematical descriptions of the second assumption [97,101]:

$$I(r_{ij,m}) = I_0 e^{-\gamma r_{ij,m}^2} \quad (4.13)$$

$$\beta(r_{ij,m}) = \beta_0 e^{-\gamma r_{ij,m}^2} \quad (4.14)$$

Where, $\boldsymbol{I_0}$ is the actual intensity of light, $\boldsymbol{\beta_0}$ is the attractiveness at r = 0, $\boldsymbol{\gamma}$ is the coefficient of light absorption that controls the variation in attractiveness and defines convergence. In most of cases, its value lie in range [0.01, 100], r is the distance between two fireflies using Cartesian distance and m is the number of local optima of an optimization problem. The distance between the $j^{th}$ and $i^{th}$ fireflies is expressed as follows:

$$r_{ij} = \left\|X_{i,m} - X_{j,m}\right\| = \sqrt{\sum_{m=1}^{k} (x_{i,m} - x_{j,m})^2}$$

$$X_{i,m} = [x_{i,1}, x_{i,2}, x_{i,3}, \ldots . x_{i,k}] \tag{4.15}$$

$$X_{j,m} = [x_{j,1}, x_{j,2}, x_{j,3}, \ldots . x_{j,k}]$$

Where, $x_{j,m}$ is the m$^{th}$ component of the spatial coordinate of the j$^{th}$ firefly and k is the number of dimensions [102]. The movement of a firefly $i$ is attracted to another more attractive (brighter) firefly $j$ is computed by [100]:

$$x_{i,m+1} = x_{i,m} + \beta(r_{ij})\left(x_{j,m} - x_{i,m}\right) + \alpha_m\,(rand - 0.5) \tag{4.16}$$

Where, $x_{i,m+1}$ is the next generation of firefly, $x_{i,m}$ and $x_{j,m}$ are the current position of fireflies, $\alpha_m$ is the randomization parameter in interval [0, 1] and rand is random number generator with numbers uniformly distributed in range [0, 1] [2,102]. Three terms make up the movements of firefly, as demonstrated by equation (4.16). The first one describes the current location of the i$^{th}$ firefly. The second describes the movement of a firefly, showing that the firefly with less brightness attracts to another brighter firefly. The third describes the firefly's random movement [36]. During the initialization phase of the algorithm, every agent in the population is assigned a solution to an optimization problem. Then, in the iterative stage, the light intensity of each agent $i$ located in position $\boldsymbol{x_i}$ is compared to the light intensity of the other agents in the population. If the light intensity of agent $i$ is less than agent $j$'s light intensity located in position $x_j$, then agent $i$ moves towards agent $j$. The agents are ranked based on the fitness value of their solutions, and the global best is updated with the most recent one (if applicable). [100,101].

## 2.4 Modified Firefly Algorithm

The Firefly algorithm is a simple to use and effective technique. For multimodal problems, researches reveal that it is sluggish to converge and easily falls into a local optimum. Furthermore, updates are made solely based on the current performance without retaining any memory of previous best solutions or performances. That could result in the loss of better solutions. Moreover, because the parameters are fixed, the search behavior remains constant throughout all iterations for any condition [103]. The search of FA is evaluated by the attraction between any two different fireflies. Different settings of the randomization parameter α and attractiveness coefficient $\beta_0$ parameters may result in different performance. Authors in [104] proposed modifications on the attraction parameters of the standard FA to obtain global solution by updating brightness of the firefly and to avoid the distance between individual fireflies from being too far. However, the attractiveness between $r^{th}$ and $n^{th}$ fireflies is given as follows:

$$\beta(r_{ij}) = \beta_{\min r,j} + (\beta_{\max\ r,j} - \beta_{\min r,j})\ e^{-\gamma r_{ij}^2} \quad (4.17)$$

Where βmin and βmax are user-supplied values and are taken as 0.2 and 1, respectively. Even if the distance is too far, $\boldsymbol{e^{-\gamma r_{ij}^2}}$ → 0, the attraction between them can be the βmin. The parameter α, which generally has values between 0 and 1, is essential in controlling the random movements to get a solution. A large value of α will have a low degree of accuracy while searching for an optimal value since the firefly's random movement spreads out and does not lead to the intended point. On the other hand, a small α will produce a good convergence rate for the displacement of the firefly moving in the desired direction [97]. Authors in [102] modified α using equation (4.19):

$$delta = 1 - \left(\frac{10^{-4}}{0.9}\right)^{\frac{1}{maxgen}} \quad (4.18)$$

$$\alpha = (1 - \text{delta}) * \alpha_0 \quad (4.19)$$

The flow chart of the modified FA is shown in Figure D.6.

## 2.5 Standard Genetic Algorithm

Genetic Algorithm (GA) was developed by Holland in the 1960s and further analyzed by Goldberg in 1989 [105]. GA is optimization algorithm inspired by the principles of natural evolution and natural selection and the idea of the ‘‘survival of the fittest’’ [40,82]. The process begins with a population of solutions randomly generated, where the ones with higher fitness are given more preference for being chosen as parents to create new solutions (offspring) for the subsequent generation [106]. Similar to any other optimization technique, GA starts by identifying the variables for optimization and the fitness function (objective function) [82]. The next step is to evaluate each chromosome's fitness value for the present generation. The GA selects a few chromosomes and utilizes them to produce the next generation in order to evolve the existing population and reach at an optimal solution, proportional to fitness value. The crossover and mutation operators are used to create new individuals in the decision space for the chosen pair of chromosomes [107]. After a predetermined number of generations, the process will be terminated. Depending on the complexity of the system and the size of the population, the required number of generations differs from system to system. The pseudocode demonstrated in Figure D.7 represents the basic steps of the GA. Figure D.8 depicts the GA's flowchart [108].

## 2.6 Constraint-Handling Technique

It is necessary to change the original constrained problem into an unconstrained one to solve a constrained optimization problem. The simplest and most widely used optimization techniques for handling constraints are transformation methods [82]. Different approaches, like Karush-Kuhn-Tucker (KKT) [109] and the death penalty function [24], have been suggested to address and satisfy the constraints of the coordination problem. Because the other approaches need derivations or are difficult to model, the penalty functions are frequently utilized [8].

The penalty method involves augmenting the objective function with a penalty term that penalizes infeasible solutions that violate the constraints [4]. Relay coordination constraints and relay characteristic constraints are incorporated into the objective function of the coordination problem using the penalty method, as illustrated in equation (4.20). In case any constraint is violated, a penalty is added to the objective function value. The penalty factor is typically set to a large value as the objective function is in a minimization form.

$$\mathbf{OF} = \sum_{i=1}^{\mathbf{n}} \mathbf{t}_i + \sum_{l=1}^{\mathbf{k}} \mathbf{P}(\boldsymbol{l}) \quad \mathbf{(4.20)}$$

Where k is the number of relay pairs, the penalty term $\boldsymbol{P}(\boldsymbol{l})$ is given by the following equation:

$$\mathrm{P}(l) = \mu \sum_{i=1}^{\mathrm{m}} H_i[\varphi_i(l)]\varphi_i^2(l) + v \sum_{j=1}^{\mathrm{r}} H_j[\psi_j(l)]\psi_j^2(l) \quad (4.21)$$

Depending on the required level of solution quality, the values of μ and v, which are penalty constants or penalty factors, should be sufficiently large with μ >> 1 and $v \geq 0$. $\varphi_i$ and $\psi_j$ represent the quality and inequality constraints, respectively. m is the number of quality constraints, while r is the number of inequality constraints. $H_i[\varphi_i(l)]$ and $H_j[\psi_j(l)]$ are index functions. More specifically,

$$\boldsymbol{H_i}[\boldsymbol{\varphi_i}(\boldsymbol{l})] = \begin{Bmatrix} \mathbf{1}, & \boldsymbol{\varphi_i}(\boldsymbol{l}) \neq \mathbf{0} \\ \mathbf{0}, & \boldsymbol{\varphi_i}(\boldsymbol{l}) = \mathbf{0} \end{Bmatrix} \quad \mathbf{(4.22)}$$

Similarly,

$$\boldsymbol{H_j}[\boldsymbol{\psi_j}(\boldsymbol{l})] = \begin{Bmatrix} \mathbf{1}, & \boldsymbol{\psi_j}(\boldsymbol{l}) > \mathbf{0} \\ \mathbf{0}, & \boldsymbol{\psi_j}(\boldsymbol{l}) \leq \mathbf{0} \end{Bmatrix} \quad \mathbf{(4.23)}$$

It is shown that the $P(l)$ has a value of zero when individuals are feasible, and a positive value when there is a violation of constraints. During the minimization process, μ and $v$ increase the relevance of the objective function's value. To attain optimal solutions with zero penalties, μ and $v$ are typically given relatively high values [4]. Their range usually set between $10^3$ and $10^{15}$ [110].

### 2.7 Proposed FA-GA Approach for Coordination Problem

The optimization algorithm performance can be enhanced by transforming the current solution into one or more improved solutions. A combination between modified FA and GA techniques is used to perform this improvement. In this hybrid method, the master meta-heuristic is the modified FA and the GA is subordinate to it. It comprises of two stages. The modified FA operates in two stages. The first stage is aimed at exploring the search space to identify the most promising region. In the second stage, the GA is incorporated to investigate the search space further (beginning with the FA's solution) and generate improved solutions to improve global search while avoiding getting trapped in multiple local optima. The main idea behind using GA is due to its genetic operators, crossover and mutation in generating new solutions. The best solutions generated by GA are considered to be the best solutions at all. The pseudo-code in Figure D.9 illustrates the structure of the hybrid FA-GA. Figure D.10 illustrates the hybrid FA-GA flowchart.

### 2.8 Testing Systems

The proposed methods are applied to a four power systems IEEE 3-bus, 6-bus, 9-bus, and 15-bus networks. These networks are employed to verify the efficacy of the suggested optimization techniques.

#### 2.8.1 System I: IEEE 3-bus Network

To assess the effectiveness of the proposed MFA, GA, and FAGA algorithms in minimizing the operating time of directional overcurrent relays, the standard IEEE 3-bus network is utilized as the first test case. Figure E.1 depicts its component parts, which are 3 buses, 3 power generators, 3 branches, and 6 relays. This case is presented as a formulation of linear and nonlinear programming. Tables E.1 and E.2, respectively, present the results of 3-short circuits and the CT ratios of the relays in the IEEE 3-bus system. The lower and upper values for TMS and PS are set at 0.1 and 1.1 and 1.5 and 5.0, respectively. The CTI value is set to 0.2 seconds, and the time bounds for the primary relays' minimum and maximum operating times are set to 0.1 and 0.5, respectively [26,33].

For this system, there will be 12 design variables and 36 constraints in the coordination problem, the standard optimization model of the optimization problem can be expressed as follows:

$min_{TMS,PS}\ Z(TMS_1, \ldots, TMS_6, PS_1, \ldots, PS_6)$ Objective Function/General expression

Subjected to (refer to equations 4.4, 4.6 4.9 and 4.10) [26,33]:

$$0.1 - t_{i,k}^{pri} \leq 0$$

$$t_{i,k}^{pri} - 0.5 \leq 0$$

$$t_{i,k}^{pri} + 0.2 - t_{j,k}^{back} \leq 0$$

$$0.1 \leq TMS_i \leq 1.1$$

$$1.5 \leq PS_i \leq 5$$

The objective function can be expanded as shown in equation (4.1):

$$OF = \min\,(t_1^{pri} + t_2^{pri} + t_3^{pri} + t_4^{pri} + t_5^{pri} + t_6^{pri})$$

Where (refer to equation 4.12):

$$t_1^{pri} = \frac{0.14 * TMS_1}{\left(\frac{1978.9}{\left(\frac{300}{5}\right)PS_1}\right)^{0.02} - 1}$$

$$t_2^{pri} = \frac{0.14 * TMS_2}{\left(\frac{1525.7}{\left(\frac{200}{5}\right)PS_2}\right)^{0.02} - 1}$$

$$t_3^{pri} = \frac{0.14 * TMS_3}{\left(\frac{1683.9}{\left(\frac{200}{5}\right)PS_3}\right)^{0.02} - 1}$$

$$t_4^{pri} = \frac{0.14 * TMS_4}{\left(\frac{1815.4}{\left(\frac{300}{5}\right)PS_4}\right)^{0.02} - 1}$$

$$t_5^{pri} = \frac{0.14 * TMS_5}{\left(\frac{1499.66}{\left(\frac{200}{5}\right)PS_5}\right)^{0.02} - 1}$$

$$t_6^{pri} = \frac{0.14 * TMS_6}{\left(\frac{1766.3}{\left(\frac{400}{5}\right)PS_6}\right)^{0.02} - 1}$$

Subjected to (refer to equations 4.4, 4.6 4.9 and 4.10):

$$\frac{0.14 * TMS_1}{\left(\frac{1978.9}{\left(\frac{300}{5}\right)PS_1}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_5}{\left(\frac{175}{\left(\frac{200}{5}\right)PS_5}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_2}{\left(\frac{1525.7}{\left(\frac{200}{5}\right)PS_2}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_4}{\left(\frac{545}{\left(\frac{300}{5}\right)PS_4}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_3}{\left(\frac{1683.9}{\left(\frac{200}{5}\right)PS_3}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_1}{\left(\frac{617.22}{\left(\frac{300}{5}\right)PS_1}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_4}{\left(\frac{1815.4}{\left(\frac{300}{5}\right)PS_4}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_6}{\left(\frac{466.17}{\left(\frac{400}{5}\right)PS_6}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_5}{\left(\frac{1499.66}{\left(\frac{200}{5}\right)PS_5}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_3}{\left(\frac{384}{\left(\frac{200}{5}\right)PS_3}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_6}{\left(\frac{1766.3}{\left(\frac{400}{5}\right)PS_6}\right)^{0.02} - 1} + 0.2 - \frac{0.14 * TMS_2}{\left(\frac{145.34}{\left(\frac{200}{5}\right)PS_2}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_1}{\left(\frac{1978.9}{\left(\frac{300}{5}\right)PS_1}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_2}{\left(\frac{1525.7}{\left(\frac{200}{5}\right)PS_2}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_3}{\left(\frac{1683.9}{\left(\frac{200}{5}\right)PS_3}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_4}{\left(\frac{1815.4}{\left(\frac{300}{5}\right)PS_4}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_5}{\left(\frac{1499.66}{\left(\frac{200}{5}\right)PS_5}\right)^{0.02} - 1} \leq 0$$

$$0.1 - \frac{0.14 * TMS_6}{\left(\frac{1766.3}{\left(\frac{400}{5}\right)PS_6}\right)^{0.02} - 1} \leq 0$$

$$\frac{0.14 * TMS_1}{\left(\frac{1978.9}{\left(\frac{300}{5}\right)PS_1}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$\frac{0.14 * TMS_2}{\left(\frac{1525.7}{\left(\frac{200}{5}\right)PS_2}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$\frac{0.14 * TMS_3}{\left(\frac{1683.9}{\left(\frac{200}{5}\right)PS_3}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$\frac{0.14 * TMS_4}{\left(\frac{1815.4}{\left(\frac{300}{5}\right)PS_4}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$\frac{0.14 * TMS_5}{\left(\frac{1499.66}{\left(\frac{200}{5}\right)PS_5}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$\frac{0.14 * TMS_6}{\left(\frac{1766.3}{\left(\frac{400}{5}\right)PS_6}\right)^{0.02} - 1} - 0.5 \leq 0$$

$$0.1 \leq TMS_1 \leq 1.1$$

$$0.1 \leq TMS_2 \leq 1.1$$

$$0.1 \leq TMS_3 \leq 1.1$$

$$0.1 \leq TMS_4 \leq 1.1$$

$$0.1 \leq TMS_5 \leq 1.1$$

$$0.1 \leq TMS_6 \leq 1.1$$

$$1.5 \leq PS_1 \leq 5.0$$

$$1.5 \leq PS_2 \leq 5.0$$

$$1.5 \leq PS_3 \leq 5.0$$

$$1.5 \leq PS_4 \leq 5.0$$

$$1.5 \leq PS_5 \leq 5.0$$

$$1.5 \leq PS_6 \leq 5.0$$

### 2.8.2 System II: IEEE 6-bus Network

Figure E.2 depicts the single line diagram of IEEE 6-bus network. There are 7 branches, 4 power generators, and 14 relays in the single-line diagram. The point of the proposed calculation for this case is to arrange the settings of 14 relays and the main goal is to obtain the optimum TMS and PS settings. At the close end of each relay (close in faults) three phase short circuit are connected. Table E.3 presents the primary/backup relay (P/B) relay pairs and the close in short circuit currents. The relays' CT ratios are presented in Table E.4. The CTI value is selected as 0.2-sec. This test system has 76 constraints in total, including 14 inequality constraints for the minimum operating times, 14 inequality constraints for the maximum operating times, 20 inequality constraints for selectivity criteria, 14 side constraints for the TMS, and 14 side constraints for the PS.

### 2.8.3 System III: IEEE 9-bus Network

The third system investigated in this study is the IEEE 9-bus network shown in Figure E.3. It consists of 9 buses, one power generator, 12 branches and 24 directional overcurrent relays. This system is considered as NLP formulation. Additionally, the lower and upper bounds of TMS have been set at 0.1 and 1.2, respectively. Meanwhile, the lower and higher bounds of PS have been defined at 0.5 and 2.5, respectively. Also, for a justified comparison, the value of the coordination time interval is set as 0.2-sec. The time bound for the minimum operational time of primary relays is set as 0.2. To complete the analysis, the three-phase short circuit currents for the primary and backup relays are provided in Table E.5 and All relays use a CT ratio of 500/1. There are a total of 128 constraints for this test system: 32 inequality constraints for selectivity criteria, 24 inequality constraints for the minimum and maximum operating times, 24 side constraints for the TMS, and 24 side constraints for the PS.

### 2.8.4 System IV: IEEE 15-bus Network

The system shown in Figure E.4 has a high level of distributed generation (DG) penetration, consisting of 15 buses, 21 branches, and 42 relays. The fault currents measured by primary and backup relays are given in Table E.6 [33]. For the directional overcurrent relays setting, the CT ratios are provided in Table E.7. Moreover, the upper and lower limits for TMS are set to 0.1 and 1.2, respectively, while the upper and lower limits for PS variable are set to 0.5 and 2.5, respectively [2]. A 0.2-sec coordination interval is considered. The test system comprises 250 constraints, which include 82 inequality constraints for selectivity criteria, 42 inequality constraints for the minimum allowable operating time, 42 inequality constraints for the maximum allowable operating time, 42 side constraints for TMS, and 42 side constraints for PS.

# Chapter Three

# Results and Discussions

## 3.1 Introduction

This chapter provides the results achieved for the directional overcurrent relays by the proposed algorithms. To demonstrate the efficacy of the suggested modified firefly algorithm (MFA), genetic algorithm (GA) and hybrid firefly-genetic algorithm (FAGA), a comparison with other optimization techniques is provided. Four standard networks, including the IEEE 3-bus, 6-bus, 9-bus, and 15-bus networks, are used to test the proposed methods. The overall net gain in time and the percentage improvement performance obtained by the suggested methods for each test system are presented. An accurate simulation program is developed using the MATLAB software to obtain the results.

## 3.2 Test System I: IEEE 3-bus Network

This network is experimented by LP, and NLP formulations. In LP formulation the only decision variable is TMS, which is continuous lying in [0.1, 1.1]. The PS values are fixed constants given in Table 3.1. PS and TMS are regarded as the design variables in the NLP formulation, which lies in [1.5, 5.0] and [0.1, 1.1] respectively, and both of them are continuous values.

**Table 3.1**

*The IEEE 3-bus network's PS values for the relays*

| Relay Number | PS |
|---|---|
| 1 | 5.0 |
| 2 | 1.5 |
| 3 | 5.0 |
| 4 | 4.0 |
| 5 | 2.0 |
| 6 | 2.5 |

### 3.2.1 Linear Programming Formulation

Table 3.2 provides the optimum settings of TMS achieved by MFA, GA and FAGA. Other methods that proposed for this system are presented to make comparison. It was observed that the proposed methods achieved superior results when compared to other algorithms. Figure 3.1 shows the graphical illustration of the optimized minimum total operating time obtained by the proposed methods in comparison to the literature. The overall net gain in time achieved by the proposed methods is presented in Table 3.3, which reveals the superiority of the proposed methods over other algorithms mentioned in the literature. The percentage performance in the operating time at 3-bus test system yielded by the proposed methods is presented in Figure 3.2, which indicates an enhancement of relay operating time using the proposed methods.

**Table 3.2**

*TMS values by LP formulation for the IEEE 3-bus network*

| Method | Time Multiplier Settings (TMS) | | | | | | Fitness |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | |
| Simplex [109] | 0.100000 | 0.136400 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.92580 |
| LP [37] | 0.100000 | 0.136400 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.92580 |
| PSO [37] | 0.100000 | 0.136400 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.92580 |
| Seeker [48] | 0.100000 | 0.136400 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.92580 |
| ABC [68] | 0.100000 | 0.136400 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.92580 |
| OJaya [4] | 0.100000 | 0.100000 | 0.1000 | 0.1000 | 0.129800 | 0.1000 | 1.78040 |
| HCSO [111] | 0.100000 | 0.100000 | 0.1000 | 0.1000 | 0.100000 | 0.1000 | 1.78040 |
| MFA | 0.100000 | 0.100000 | 0.1000 | 0.1000 | 0.100000 | 0.1000 | 1.78039 |
| GA | 0.100016 | 0.100004 | 0.1000 | 0.1000 | 0.100002 | 0.1000 | 1.78047 |
| FAGA | 0.100000 | 0.100000 | 0.1000 | 0.1000 | 0.100000 | 0.1000 | 1.78039 |

**Figure 3.1**

*Total operation time compared to the literature for the proposed methods*

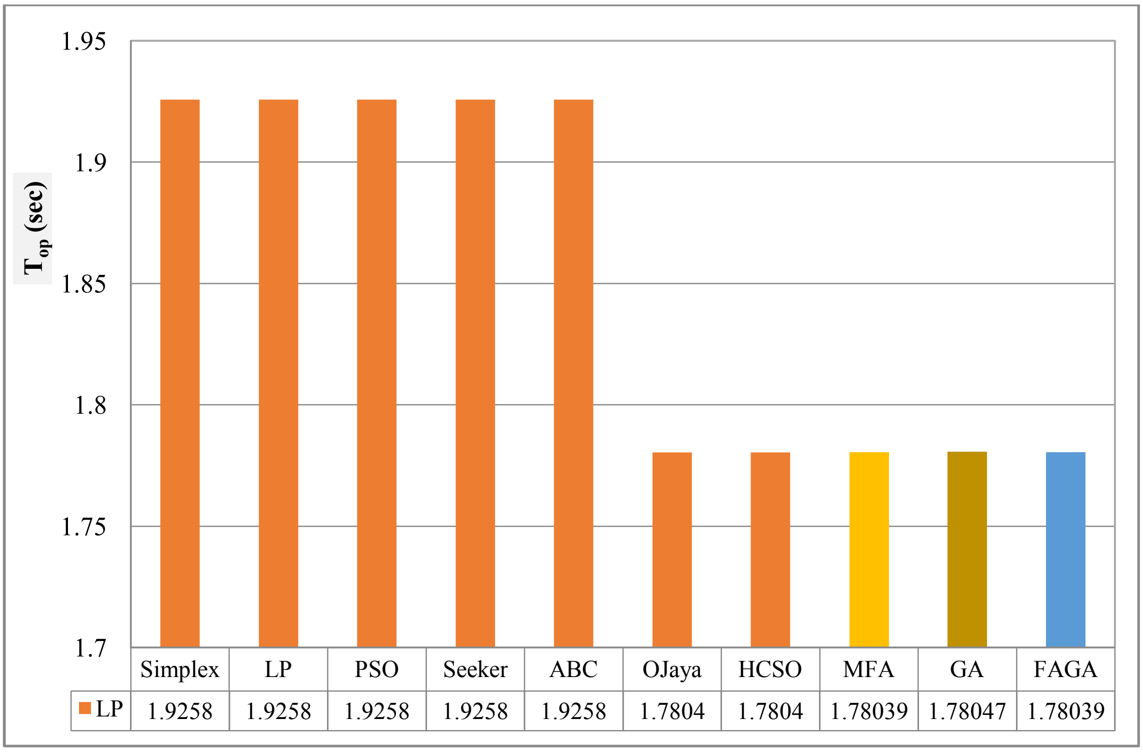


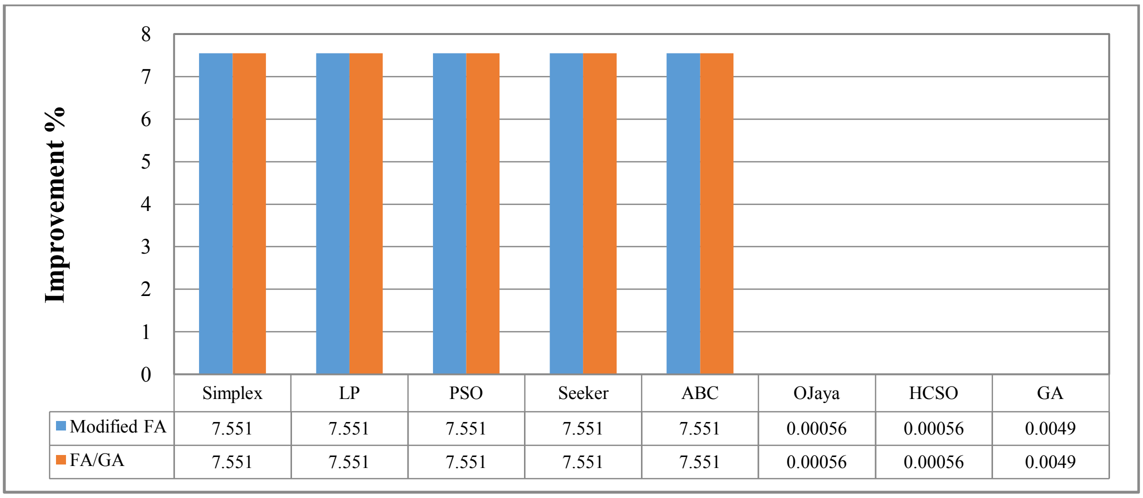
**Table 3.3**

*Comparison of total net gain in time obtained by proposed methods with the algorithms used in the literature*

| Method | $\sum \Delta(t)$ (sec) | % Improvement | Method | $\sum \Delta(t)$ (sec) | % Improvement |
|---|---|---|---|---|---|
| MFA/ Simplex | 0.14541 | 7.55100 | FAGA/Simplex | 0.14541 | 7.55100 |
| MFA/ LP | 0.14541 | 7.55100 | FAGA /LP | 0.14541 | 7.55100 |
| MFA/ PSO | 0.14541 | 7.55100 | FAGA /PSO | 0.14541 | 7.55100 |
| MFA/ Seeker | 0.14541 | 7.55100 | FAGA /Seeker | 0.14541 | 7.55100 |
| MFA/ ABC | 0.14541 | 7.55100 | FAGA /ABC | 0.14541 | 7.55100 |
| MFA/ OJaya | 0.00001 | 0.00056 | FAGA /OJaya | 0.00001 | 0.00056 |
| MFA/ HCSO | 0.00001 | 0.00056 | FAGA /HCSO | 0.00001 | 0.00056 |
| MFA/ GA | 0.00008 | 0.00490 | FAGA /GA | 0.00008 | 0.00490 |

**Figure 3.2**

*Percentage improvement of the proposed methods compared to other algorithms in the literature for IEEE 3-bus network in terms of the net relay operational time*




The CTI of each relay pair is presented in Table 3.4. It is demonstrated each backup and primary relay pair satisfy the CTI criteria and that all of them are greater than 0.2.

**Table 3.4**

*CTI using the LP formulation for the IEEE 3-bus network*

| P/R | MFA | GA | FAGA |
|---|---|---|---|
| | CTI | CTI | CTI |
| 1 | 0.52319 | 0.52375 | 0.52308 |
| 2 | 0.63712 | 0.63806 | 0.63705 |
| 3 | 0.64169 | 0.64170 | 0.64286 |
| 4 | 0.48122 | 0.48166 | 0.48140 |
| 5 | 0.83420 | 0.83452 | 0.83414 |
| 6 | 0.46982 | 0.46985 | 0.47003 |

### 3.2.2 Non Linear Programming Formulation

The optimal settings of the decision variables TMS and PS are shown in Table 3.5. A comparison of results obtained by the proposed methods and other published algorithms are also provided in Table 3.6. Figure 3.3 presents a graphical representation of the total operating time achieved by the proposed methods compared to other published techniques. The figure displays the optimized values of total operating time. The overall net gain in time achieved by the proposed methods and other published algorithms reported in the literature is depicted in Table 3.7. Figure 3.4 indicates the improvement in the relay operating time using the proposed methods.

**Table 3.5**

*Relay settings for IEEE 3-bus network by NLP formulation*

| Variables | AFA [97] | Analytic [39] | Jaya [4] | IGWO [112] | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|
| TMS 1 | 0.1143 | 0.1000 | 0.1000 | 0.10000 | 0.10000 | 0.118970 | 0.100069 |
| TMS 2 | 0.1000 | 0.1000 | 0.1000 | 0.10000 | 0.10000 | 0.100001 | 0.100000 |
| TMS 3 | 0.1074 | 0.1000 | 0.1453 | 0.10010 | 0.10000 | 0.109758 | 0.100022 |
| TMS 4 | 0.1000 | 0.1000 | 0.1000 | 0.10000 | 0.10000 | 0.107297 | 0.100033 |
| TMS 5 | 0.1000 | 0.1000 | 0.1000 | 0.10000 | 0.10000 | 0.100004 | 0.100000 |
| TMS 6 | 0.1125 | 0.1000 | 0.1000 | 0.10000 | 0.10000 | 0.100011 | 0.100000 |
| PS 1 | 1.2500 | 2.7000 | 1.5000 | 1.50000 | 2.25484 | 1.500000 | 1.945890 |
| PS 2 | 1.3400 | 2.1250 | 2.9780 | 2.61660 | 1.55414 | 1.500000 | 1.500000 |
| PS 3 | 1.2500 | 2.8750 | 1.5000 | 2.97700 | 1.80029 | 1.528990 | 1.787530 |
| PS 4 | 1.4300 | 2.3333 | 1.7841 | 1.58500 | 2.32436 | 1.500040 | 1.683100 |
| PS 5 | 1.3900 | 2.2750 | 1.8601 | 2.81690 | 1.51354 | 1.500000 | 1.500000 |
| PS 6 | 1.2500 | 1.2695 | 1.5000 | 1.50090 | 1.61407 | 1.500070 | 1.500050 |
| Fitness | 4.7636 | 1.5108 | 1.5109 | 1.47890 | 1.41858 | 1.401310 | 1.36501 |

**Table 3.6**

*Comparison of the proposed methods' percentage improvement and the overall net gain in time over the literature's algorithms*

| Method | $\sum \Delta(t)$ (sec) | % Improvement | Method | $\sum \Delta(t)$ (sec) | % Improvement |
|---|---|---|---|---|---|
| MFA/ AFA | 3.34502 | 70.22 | FAGA/AFA | 3.39859 | 71.34 |
| MFA/ Analytic | 0.09222 | 6.100 | FAGA/Analytic | 0.14579 | 9.649 |
| MFA/ Jaya | 0.09232 | 6.110 | FAGA/Jaya | 0.14589 | 9.656 |
| MFA/ IGWO | 0.06032 | 4.079 | FAGA/IGWO | 0.11389 | 7.701 |
| MFA/ GA | - | - | FAGA /GA | 0.03630 | 2.590 |

From the obtained results, it can be concluded that the suggested methods have once again outperformed their counterparts by computing a minimum value of fitness evaluation function in terms of the overall operational time of directional overcurrent relays in the IEEE 3-bus system, thereby confirming the superiority, efficiency, and robustness of the suggested algorithms.

**Figure 3.3**

*Total operation time compared to the literature for the proposed methods*

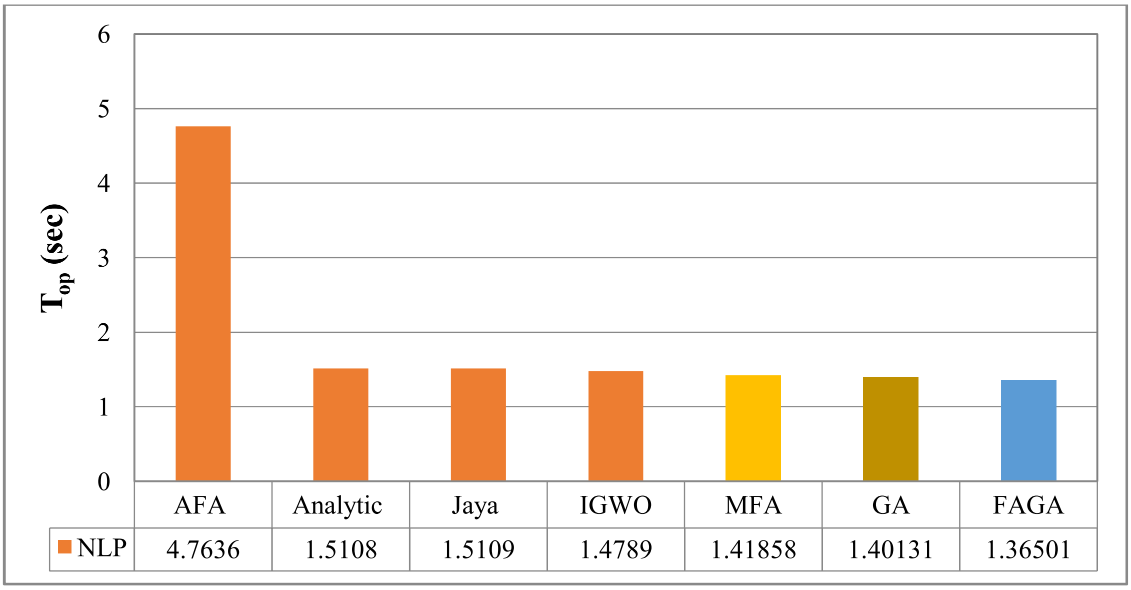
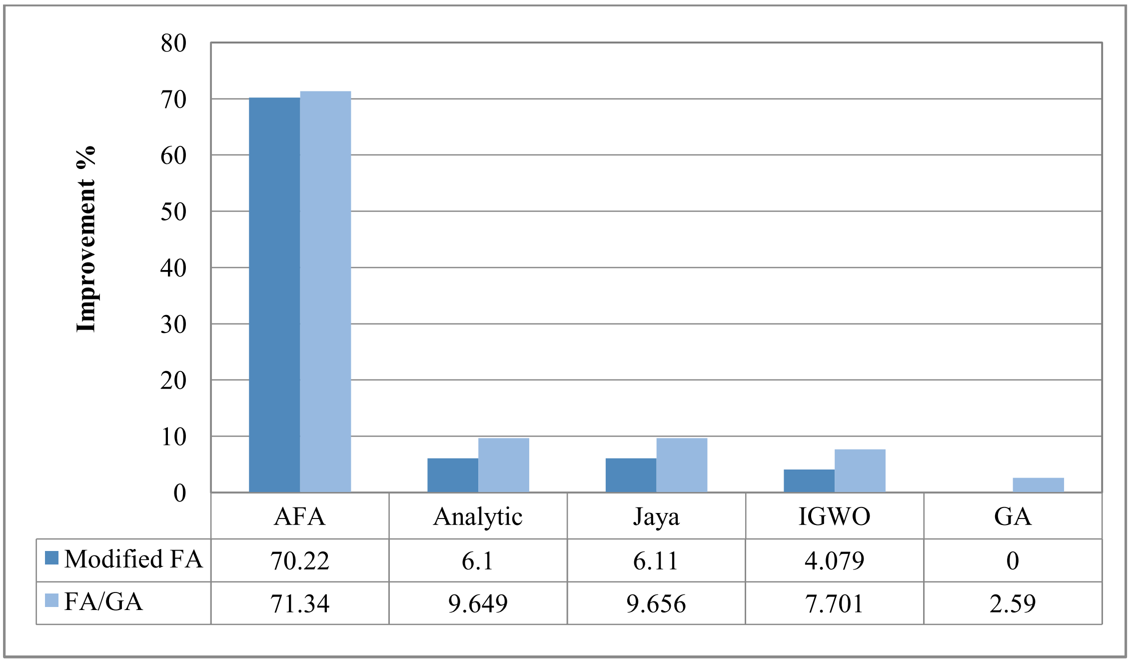


**Figure 3.4**

*Percentage improvement of the proposed methods compared to other algorithms in the literature for IEEE 3-bus network in terms of the net relay operational time*




The CTI for the six relay pairs for the IEEE 3-bus system is shown in Table 3.7. It is clear that the primary relays function first, followed by the backup relays in the case that the primary relays are not able to isolate the problem within the coordination time margin.

**Table 3.7**

*CTI using the NLP formulation for the IEEE 3-bus network*

| P/R | MFA | GA | FAGA |
|---|---|---|---|
| | CTI | CTI | CTI |
| 1 | 0.40020 | 0.38590 | 0.40602 |
| 2 | 0.29461 | 0.20003 | 0.20001 |
| 3 | 0.23977 | 0.20019 | 0.20000 |
| 4 | 0.27273 | 0.26659 | 0.27314 |
| 5 | 0.20000 | 0.20005 | 0.20000 |
| 6 | 0.55715 | 0.53164 | 0.53085 |

### 3.3 Test System II: IEEE 6-bus Network

The values of the continuous TMS in the LP formulation lie between [0.1, 1.1]. The PS values are fixed constants given in Table F.1. In the NLP formulation, the continuous variables PS and TMS both have ranges between [1.5, 5.0] and [0.1, 1.1], respectively.

### 3.3.1 Linear Programming Formulation

The optimal TMS settings obtained by the proposed methods are shown in Table F.2, along with a comparative analysis of those methods with other algorithms that have been published and are mentioned in the literature. Figure F.1 shows a graphical representation of the total operating time obtained by proposed methods with other published techniques. It is shown that the proposed methods have obtained improved results for the IEEE 6-bus test system. The assessment of total net gain in time achieved in this case by the proposed methods is shown in Table F.3 with respect to other techniques mentioned in the literature. It was found that the proposed algorithms outperform other methods in terms of net time gain while also producing results that are more satisfying and effective. The percentage improvement in the overall operating time, as compared to the literature, is shown graphically in Figure F.2, which shows that the effectiveness of the proposed techniques in improving relay operating time.

The CTI of each relay pair obtained by the proposed algorithms is shown in Table F.4. These results indicate that the CTI values are consistently higher than the lowest limit of CTI applied throughout this study.

### 3.3.2 Nonlinear Programming Formulation

This study formulates the case of the network as a nonlinear programming case. Table F.5 presents the TMS and PS's optimum settings. Figure F.3 shows the optimized values of the total operating time that result by the proposed methods.

The coordination margin achieved using the proposed techniques are shown in Table F.6. The backup relays will be activated if the primary relays fail to function, as can be observed from the table. It can be concluded that the proposed methods success to obtain the optimal relay setting that maintains the sequential operation between relay pairs.

## 3.4 Test System III: IEEE 9-bus Network

The suggested algorithms are applied to an IEEE 9-bus network. In this case, all relays are considered as numerical relays. Thus, this network is formulated as NLP. The continuous decision variables PS and TMS have ranges between [0.5, 2.5] and [0.1, 1.2], respectively. The optimized TMS and PS values obtained by the MFA, GA and

FAGA with other published techniques for this case are given in Table F.7. The overall operating time obtained using the proposed methods and other methods that have been published are depicted graphically in Figure F.4. Table F.8 presents an examination of the overall net gain in time that was achieved for this case using the proposed methods. It can be shown that the proposed methods outperform other algorithms in terms of net time gain. Figure F.5 shows the percentage improvement of the net relay operating time of the proposed methods compared to other methods in the literature.

The discrimination times for each relay pair are included in Table F.9. It has been demonstrated that the coordination time interval between the relays has been maintained, which yields good performance from the proposed techniques.

### 3.5 Test System IV: IEEE 15-bus Network

The last test system considered in this chapter is the IEEE 15-bus network. All relays are regarded as numerical relays in this case. As a result, this network is formulated as NLP. The continuous decision variables PS and TMS have ranges between [0.5, 2.5] and [0.1, 1.2], respectively. The optimized TMS and PS values obtained by the MFA, GA and FAGA with other published techniques for this case are given in Table F.10. The optimal solution found by the suggested approaches is superior to that obtained by using other techniques, as can be seen from Table F.11. Figure F.6 shows a graphical presentation of the total operating time that was achieved by utilizing the proposed techniques and other methods that have been published. Table B10 presents an examination of the overall net gain in time that was achieved for this case using the proposed methods. In comparison to other approaches mentioned in the literature, the proposed methods' percentage improvement in the net relay operating time is shown in Figure F.7. It is evident that the proposed methods provide the least objective function, which confirms to their effectiveness in resolving the coordination problem of directional overcurrent relays.

Table F.12 includes the discrimination times for each relay pair. It can be seen that the primary relays operate initially, and then, after a coordination time margin, the backup relays function in case the primary relays are failed in isolating the fault.

### 3.6 Number of Objective Function Evaluation

In order to illustrate the efficacy of the hybrid proposed algorithm, the objective function evaluation number is used to make comparison between the hybrid algorithm and the standard genetic algorithm. The number of the objective function evaluation and the percentage improvement for each simulated case are shown in Table 3.8. The results reveal the superiority of the proposed hybrid algorithm when compared to the standard GA.

**Table 3.8**

*Number of fitness evaluation for the GA and hybrid algorithms*

| Case | Method | Number of objective function evaluation | %Improvement |
|---|---|---|---|
| IEEE 3-bus LP | GA<br>FAGA | 165432<br>85454 | 48.345 |
| IEEE 3-bus NLP | GA<br>FAGA | 173656<br>81070 | 53.316 |
| IEEE 6-bus LP | GA<br>FAGA | 266000<br>121448 | 54.343 |
| IEEE 6-bus NLP | GA<br>FAGA | 281200<br>159490 | 43.282 |
| IEEE 9-bus NLP | GA<br>FAGA | 604800<br>401350 | 33.639 |
| IEEE 15-bus NLP | GA<br>FAGA | 602432<br>313440 | 47.971 |

# Chapter Four

# Conclusions and Future Works

## 4.1 Introduction

The main objective of this study was to find the optimal settings of the directional overcurrent relays using modified FA, GA and hybrid FA-GA algorithm. The algorithms were evaluated using four standard test systems. The proposed techniques were utilized to obtain the optimum relay settings and the overall operating time, which were then compared to other published techniques. To verify the superiority of the hybrid developed algorithm, the number of the objective function evaluation was used to make comparison with the standard genetic algorithm. The results indicated that the developed hybrid method outperformed the standard GA. In this chapter, the conclusions and the future works of this research are provided.

## 4.2 Conclusions

This research proposed a modified firefly algorithm and hybrid firefly-genetic algorithm to solve the directional overcurrent relays coordination problem. In modified firefly algorithm, the attractiveness coefficient and the randomization parameter are controlled to get good convergence rate. The hybrid firefly-genetic algorithm is proposed to get better solution, the two techniques are applied in a serial fashion, which divided into two stages, the modified firefly algorithm is applied in the first stage to obtain global solutions, and the results from the algorithm are used as the initial population for the genetic algorithm in the last stage to obtain better solutions. To compare the performance of the proposed methods in solving the problem, the methods are applied to the directional overcurrent relays coordination problem including IEEE 3-bus, 6-bus, 9-bus and 15-bus test systems. The results demonstrate that the proposed methods are superior to the previous approaches in obtaining the minimal total operating time of primary relays and maintaining the correct coordination between primary and backup relay pairs. The hybrid firefly-genetic algorithm achieves a better solution with fewer objective function evaluations than the standard genetic algorithm.

## 4.3 Future Works

The algorithms used in this work were tested using a single type of fault and the same standard inverse characteristic for all relays. It is advised that the proposed algorithms be tested for various standard characteristics and multiple types of faults. Additionally, the work can be expanded by using additional decision variables that are non-standard characteristics curve relays to provide the relay coordination issue more flexibility.

# List of Abbreviations

| Abbreviation | Meaning |
|---|---|
| TMS | Time Multiplier Setting |
| TD | Time Dial |
| PS | Plug Setting |
| IP | Pickup Current |
| CTI | Coordination Time Interval |
| CB | Circuit Breaker |
| CT | Current Transformers |
| PT | Potential Transformers |
| IDMT | Inverse Definite Minimum Time |
| t | Relay Operating Time In Seconds |
| TD | Time Dial, Or Time Multiplier Setting |
| Isc | Fault Current Level In Secondary Amperes |
| IPU | Tap Or Pickup Current Setting |
| C | Constant |
| α | Slope Constant |
| β | Slope Constant |
| PSM | Plug Setting Multiplier |
| RMS | Root Mean Square |
| Kld | Overload Factor That Based On The Element Being Protected. |
| Inom | Nominal Rated Current. |
| CTR | Current Transformer Ratio. |
| DR | Directional Overcurrent Relay |
| CAPE | Computer Aided Protection Engineering |
| GUI | Matlab Graphical User Interface |
| LP | Linear Programming |
| NLP | Non-Linear Programming |
| MILP | Mixed Integer Linear Programming |
| MINLP | Mixed Integer Non-Linear Programming |
| GA | Genetic Algorithm |
| PSO | Particle Swarm Optimization |
| SE | Seeker Algorithm |

| Abbreviation | Meaning |
|---|---|
| CrSA | Crow Search Algorithm |
| FA | Firefly Algorithm |
| HBA | Honey Bee Algorithm |
| DE | Differential Evolution Algorithm |
| HSA | Harmony Search Algorithm |
| ABC | Artificial Bee Colony |
| CSA | Cuckoo Search Algorithm |
| WOA | Whale Optimization Algorithm |
| WCA | Water Cycle Algorithm |
| TLBO | Teaching Learning Based Optimization Algorithm |
| GWO | Grey Wolf Optimizer |
| IGSO | Improved Group Search Optimization |
| HHO | Harris Hawk Optimization |
| Symbol | Meaning |
| SCA | Sine Cosine Algorithm |
| SFLA | Shuffled Frog Leaping Algorithm |
| SSO | Symbiotic Organism Search Technique |
| SOA | Seagull Optimization Algorithm |
| PSO-TVAC | Time Varying Acceleration Coefficient |
| HPSO | Hybridized Version Of Particle Swarm Optimization |
| SA | Simulated Annealing |
| BBO | Biogeography-Based Optimization |
| SQP | Sequential Quadratic Programming |
| MFO | Moth-Flame Optimization |
| WCMF | Water Cycle And Moth Flame Algorithm |
| GBO | Gradient-Based Optimizer |
| GSA | Gravitational Search Algorithm |
| HS-SA | Hybrid Harmony Search And Simulated Annealing |
| ILP | Interval Linear Programming |
| LSHADE | Memory-Based Linear Population Size Reduction Technique Of Success-History-Based Adaptive Differential Evolution Algorithm |
| IEC | International Electrotechnical Commission |
| IECSI | IEC Standard Inverse |

| Abbreviation | Meaning |
| --- | --- |
| OF | Objective Function |
| $TMS^{min}$ | Minimum Limit of TMS |
| $TMS^{max}$ | Maximum Limit of TMS |
| $IP^{min}$ | Minimum Limit of IP |
| $IP^{max}$ | Maximum Limit of IP |
| $PS^{max}$ | Minimum Limit of PS |
| $PS^{min}$ | Maximum Limit of PS |
| $t_{min}$ | Time Bound For The Minimum Operational Time of The Relay |
| $t_{max}$ | Time Bound For The Maximum Operational Time of The Relay |
| $t_{backup}$ | Relay Operating Time of The Backup Relays |
| $t_{primary}$ | Relay Operating Time of The Primary Relays |
| $CTI_{min}$ | The Minimum Coordination Time Interval |
| $I_{f,min}$ | Minimum Fault Current |
| KKT | Karush-Kuhn-Tucker |
| k | Number of Relay Pairs |
| μ and v | Penalty Constants or Penalty Factors |
| m | Number of Quality Constraints |
| r | Number of Inequality Constraints |
| $H_i [\varphi_i (l)]$ and $H_j [\psi_j (l)]$ | Index Functions |
| FAGA | Hybrid Firefly-Genetic Algorithm |
| AFA | Adaptive Firefly Algorithm |
| IGWO | Improved Grey Wolf Optimizer |
| MFA | Modified Firefly Algorithm |
| Symbol | Meaning |
| IFA | Improved Firefly Algorithm |

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# Appendices

## Appendix A

### IEC and IEEE standards Constants for Overcurrent Relays.

**Table A.1**

*IEC and IEEE Constants for Standard Overcurrent Relays.*

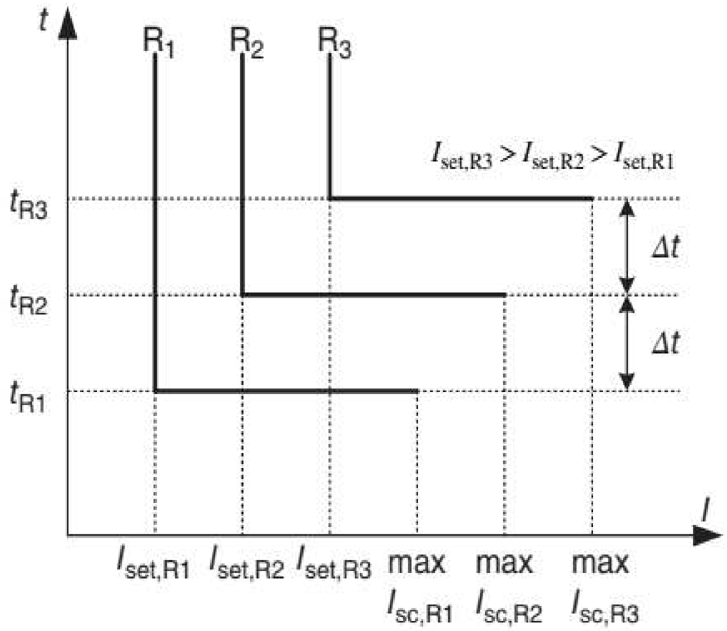
| IDMT Curve Description | α | β | C |
|---|---|---|---|
| **IEC** | | | |
| STI | 0.05 | 0.04 | |
| SI | 0.14 | 0.02 | |
| VI | 13.5 | 1 | 0 |
| EI | 80 | 2 | |
| LTI | 120 | 1 | |
| **IEEE** | | | |
| MI | 0.0515 | 0.02 | 0.114 |
| VI | 19.61 | 2 | 0.491 |
| EI | 28.2 | 2 | 0.1217 |
| I | 44.6705 | 2.0938 | 0.8983 |
| SI | 1.3315 | 1.2969 | 0.16965 |
| LI | 28.0715 | 1 | 10.9296 |

## Appendix B

## Time-delay Coordination for different types of overcurrent relay

**Figure B.1**

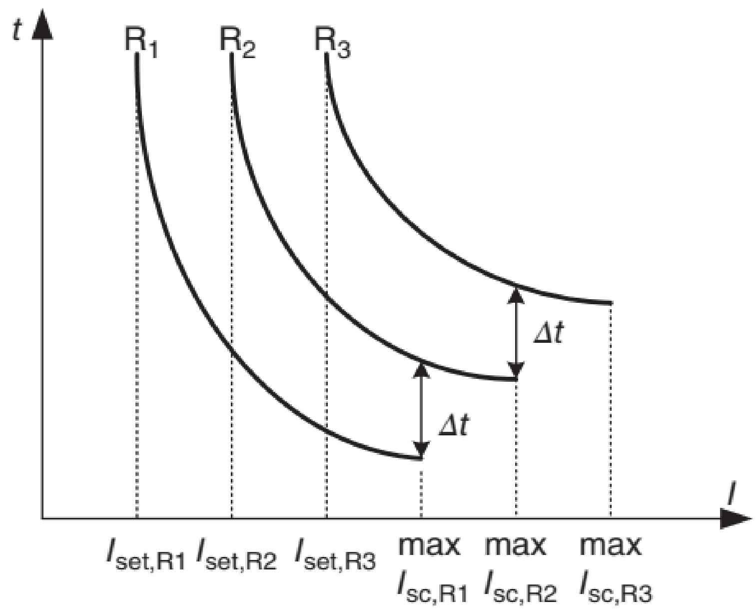
*Time-delay Coordination for Definite-Time Protection*




*Note*: Adapted from [15].

**Figure B.2**

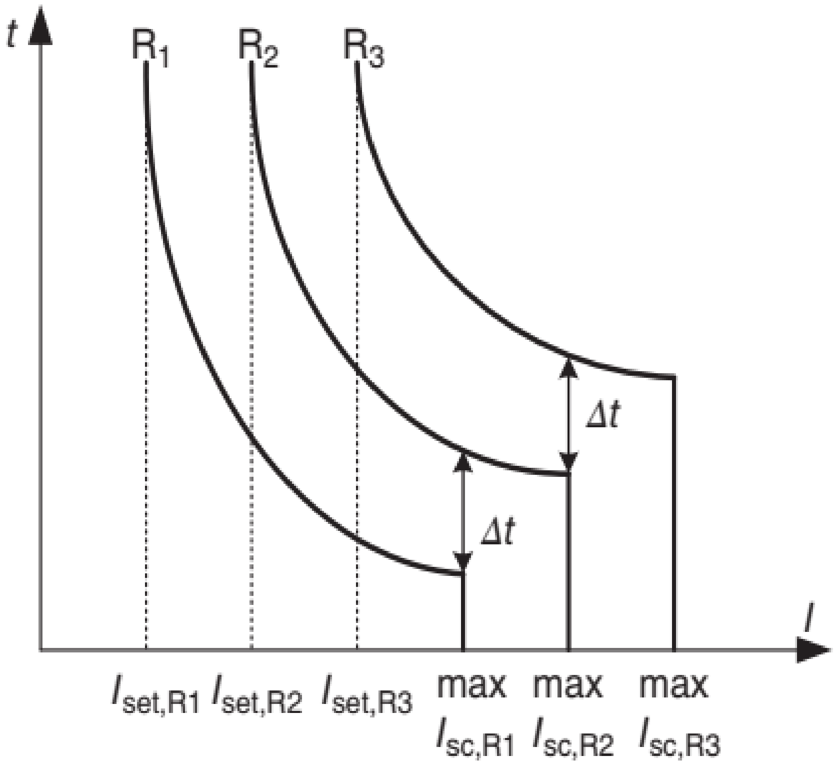
*Time-delay Coordination for Inverse-Time Protection*




*Note*: Adapted from [15].

**Figure B.3**

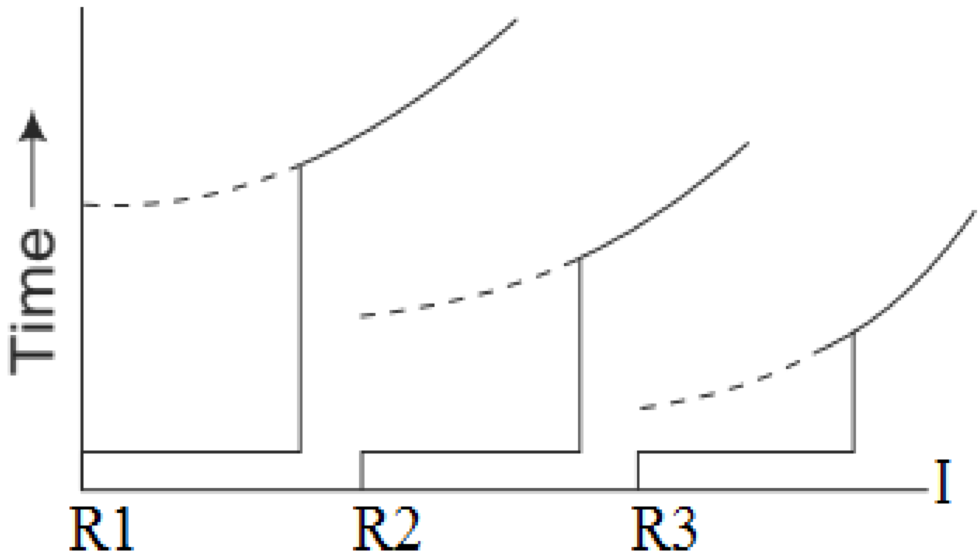
*Time-delay Coordination for Combined Inverse-Time and Instantaneous Protection*




*Note*: Adapted from [15].

**Figure B.4**

*Current-based Coordination for Combined Inverse-Time and Instantaneous Protection*




*Note*: Adapted from [19].

# Appendix C

## Figures related to optimization algorithms section

**Figure C.1**

*Classifications of optimization techniques*

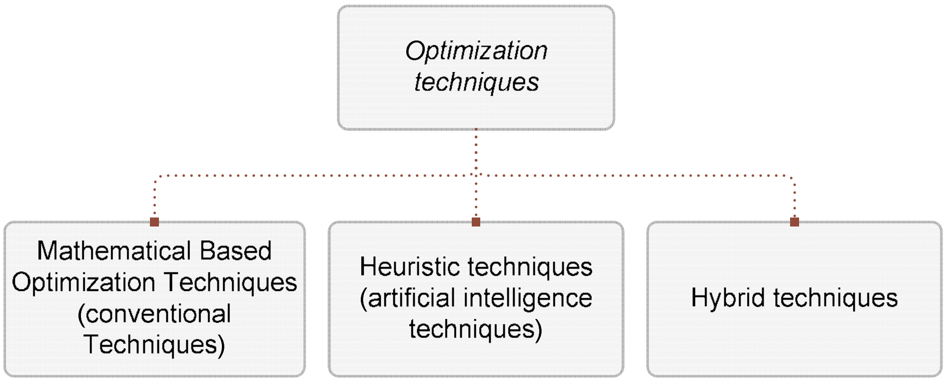
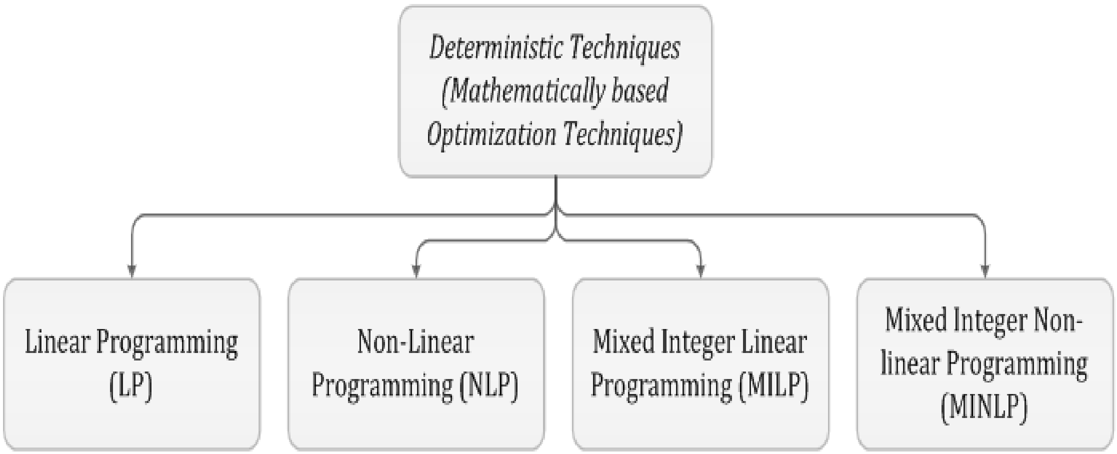



**Figure C.2**

*Mathematically-based optimization methods*

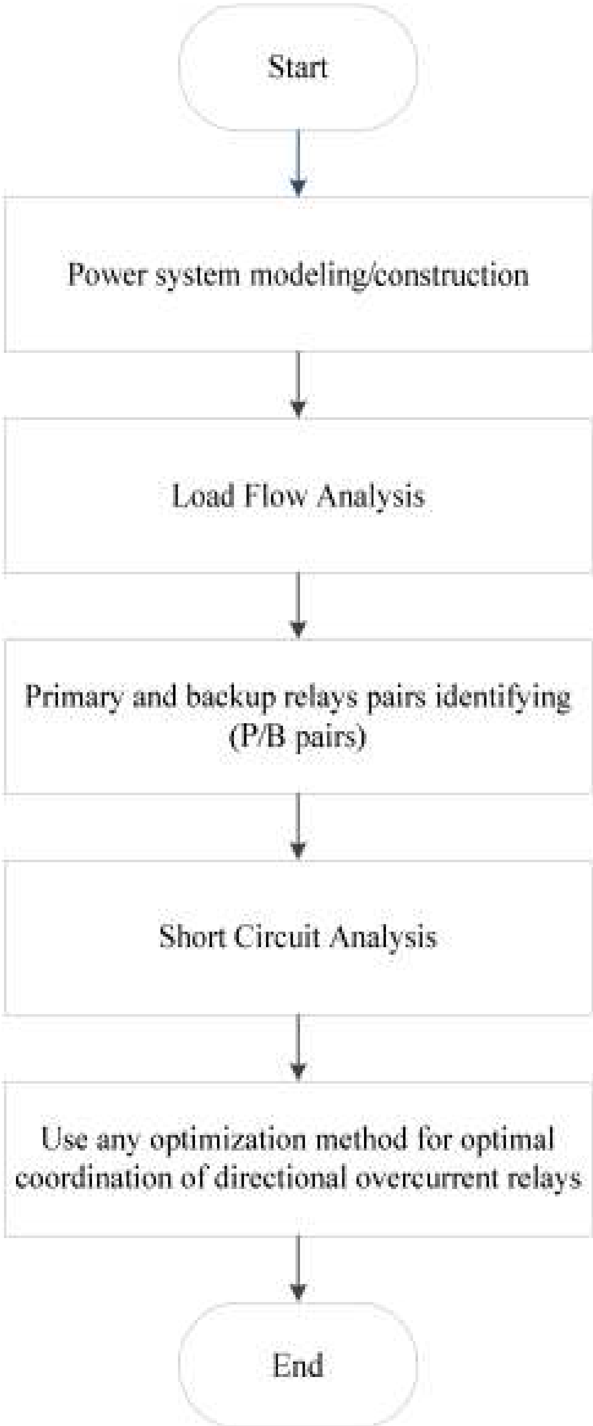


# Appendix D

## Figures related to Methodology Section

**Figure D.1**

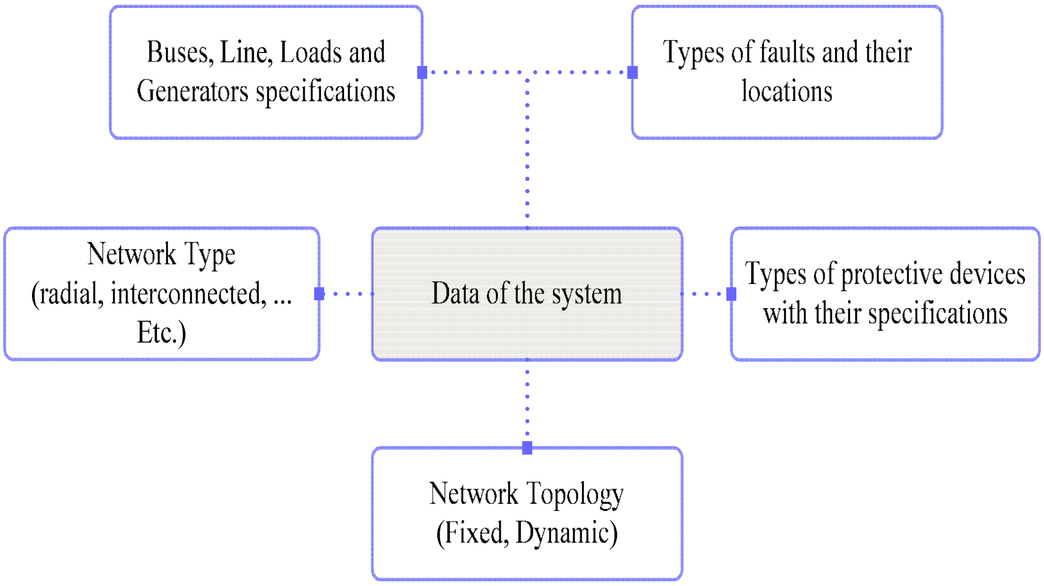
*General procedures for optimally coordination directional overcurrent relays*




*Note*: Adapted from [99].

**Figure D.2**

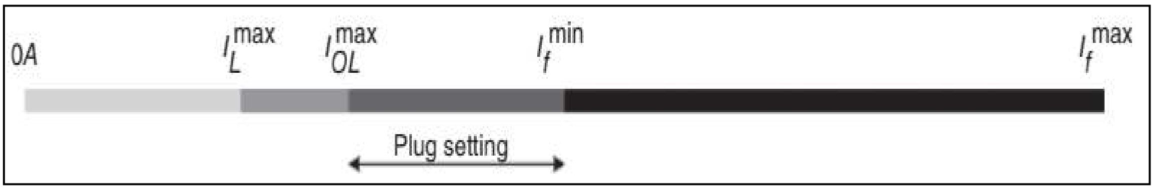
*Information needed for modeling the power system*




*Note*: Adapted from [99].

**Figure D.3**

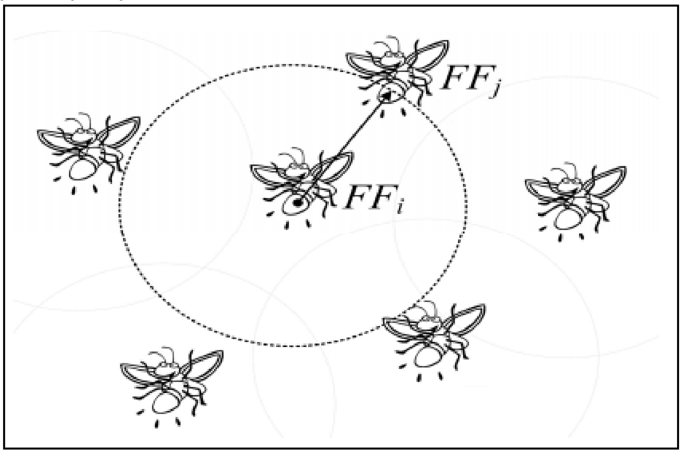
*The available range of PS*




*Note*: Adapted from [99].

**Figure D.4**

*Representation of the fireflies*




*Note*: Adapted from [35].

**Figure D.5**

*FA Pseudo Code*

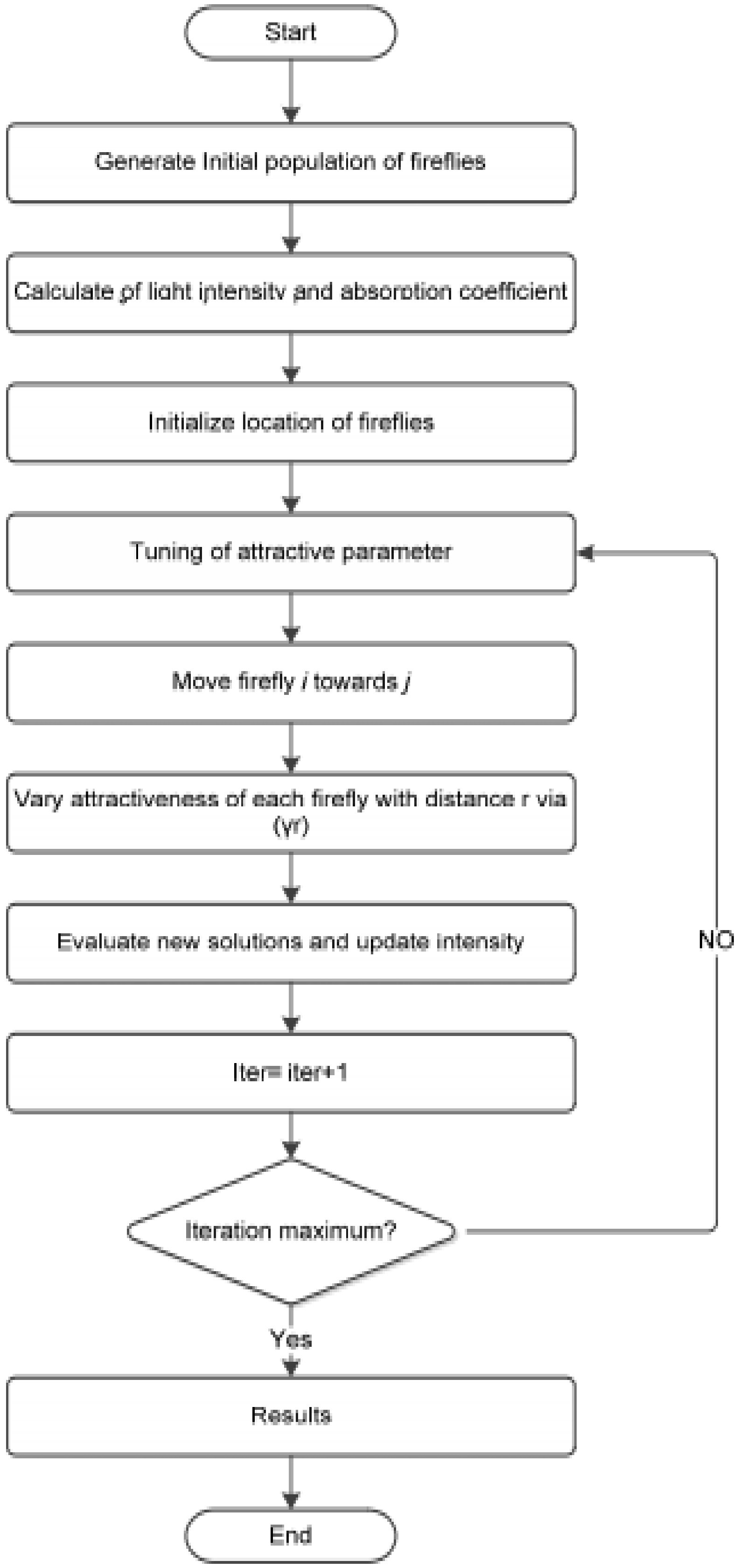
1. Initialize algorithm parameters (number of fireflies (n), generation number (nGer), absorption coefficient ($\gamma$), attractiveness ($\beta_{min}$ and $\beta_{max}$) and the randomness strength ($\alpha_0$))
2. Objective function $f(x)$, $x=(x_1,\ldots,x_d)^T$
3. Generate initial population of fireflies $x_i$ (i= 1, 2, … ,n)
4. Light intensity $I_i$ in $x_i$ is determined by $f(x_i)$
5. While (t < nGer)

        for $i$ = 1:n
          for $j$ = 1:$i$
              if ($I_j > I_i$), then move $i$ towards $j$ in d-dimension; End if
              Attractiveness varies with distance r vie exp[-γr]
              Evaluate solutions and update light intensity
          End for $j$
        End for $i$

6. Rank the fireflies and find the best global solution
7. End while
8. Postprocess results and visualization

**Figure D.6**

*Flowchart of the modified FA*



## Figure D.7

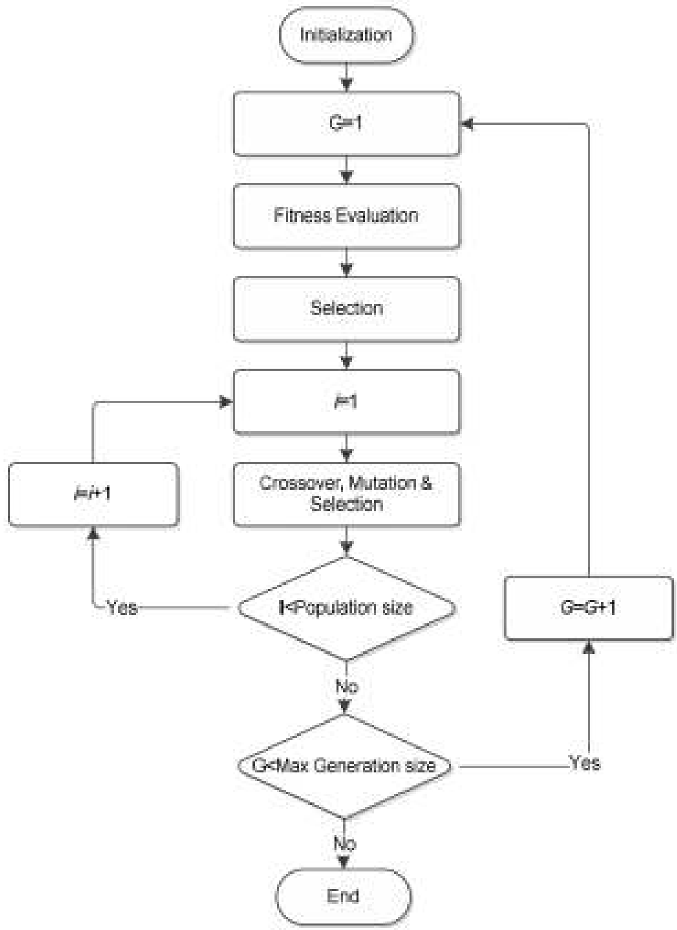
*GA Pseudo Code*

1. Initialize algorithm parameters (number of population (nPop), generation number (nGer), Crossover probability (Pc), Mutation probability (Pm))
2. Objective function $f(\mathrm{x})$, $x=(x_1,\dots,x_d)^T$
3. $i=0$
4. Generate initial population of chromosomes $x_i$ ($i=1, 2, \dots, n$)
5. Fitness function is determined by $f(x_i)$
6. While (t < nGer)
   - $i=i+1$
   - Select parents from population
   - Apply crossover mechanism with probability Pc
   - Apply mutation mechanism with probability Pm
7. Rank individuals and find the best global solution
8. End while
9. Postprocess results and visualization

*Note*: Adapted from [108].

## Figure D.8

*Flowchart of the GA*




*Note*: Adapted from [108].

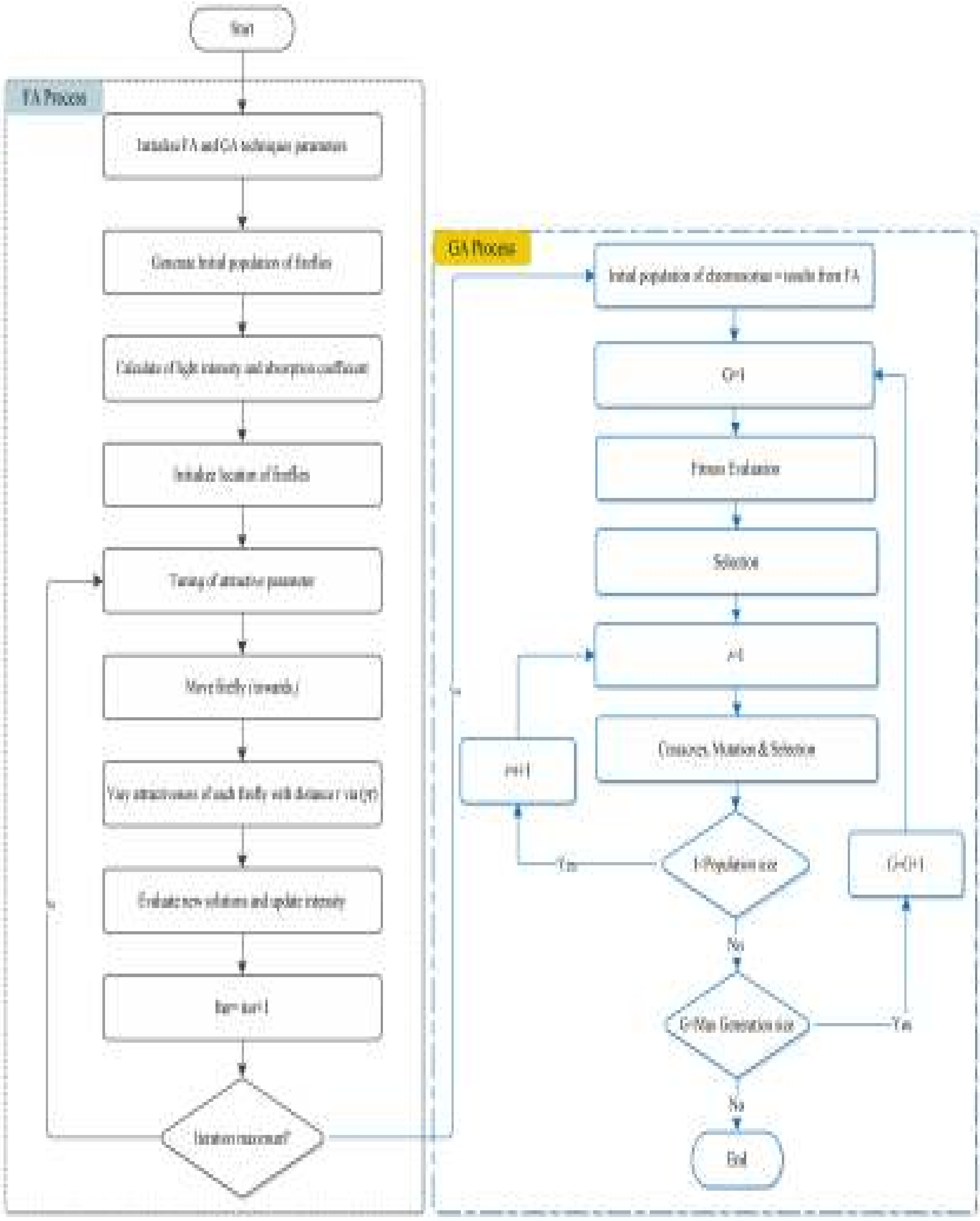
**Figure D.9**

*Hybrid FA-GA Pseudo Code*

| | **Stage 1: FA Starting** |
|---|---|
| 1. | Initialize FA and GA parameters (number of fireflies (n), generation number of FA (nGerFA), absorption coefficient ($\gamma$), attractiveness ($\beta_{min}$ and $\beta_{max}$) the randomness strength ($\alpha$), number of population (nPop), generation number of GA (nGerGA), Crossover probability (Pc) and Mutation probability (Pm)) |
| 2. | Objective function $f$(x), $x=(x_1,\ldots,x_d)^T$ |
| 3. | Generate initial population of fireflies $x_i$ (i= 1, 2, … ,n) |
| 4. | Determine light intensity $I_i$ in $x_i$ by $f(x_i)$ |
| 5. | While (t < nGerFA) |
| | for $i$ = 1:n |
| | for $j$ = 1:n |
| | if ($I_j$ > $I_i$), then move $i$ towards $j$ in d-dimension; End if |
| | Attractiveness varies with distance r vie exp[$-\gamma r^2$] |
| | Evaluate solutions and update light intensity |
| | End for $j$ |
| | End for $i$ |
| 6. | Rank the fireflies and find the best global solution |
| 7. | End while |
| 8. | Results from FA |
| 9. | End FA |
| | **Stage 2: GA Starting** |
| 10. | $i$=0 |
| 11. | initial population of chromosomes P(0) = results from FA |
| 12. | Determine fitness function |
| 13. | While (t < nGerGA) |
| | $i$=$i$+1 |
| | Select parents from population |
| | Apply crossover mechanism with probability Pc |
| | Apply mutation mechanism with probability Pm |
| | Fitness calculation |
| 14. | Rank individuals and find the best global solution |
| 15. | End while |
| 16. | Postprocess results and visualization |

**Figure D.10**

*Flowchart of the hybrid FA-GA technique*



# Appendix E

## Test Systems Specifications

**Test System II: IEEE 3-bus**

**Table E.1**

*Three-phase short circuit current of IEEE 3-bus network*

| P/B | Primary Relay | Short circuit Current (A) | Backup Relay | Short circuit Current (A) |
|---|---|---|---|---|
| 1 | 1 | 1978.90 | 5 | 175.00 |
| 2 | 2 | 1525.70 | 4 | 545.00 |
| 3 | 3 | 1683.90 | 1 | 617.22 |
| 4 | 4 | 1815.40 | 6 | 466.17 |
| 5 | 5 | 1499.66 | 3 | 384.00 |
| 6 | 6 | 1766.30 | 2 | 145.34 |

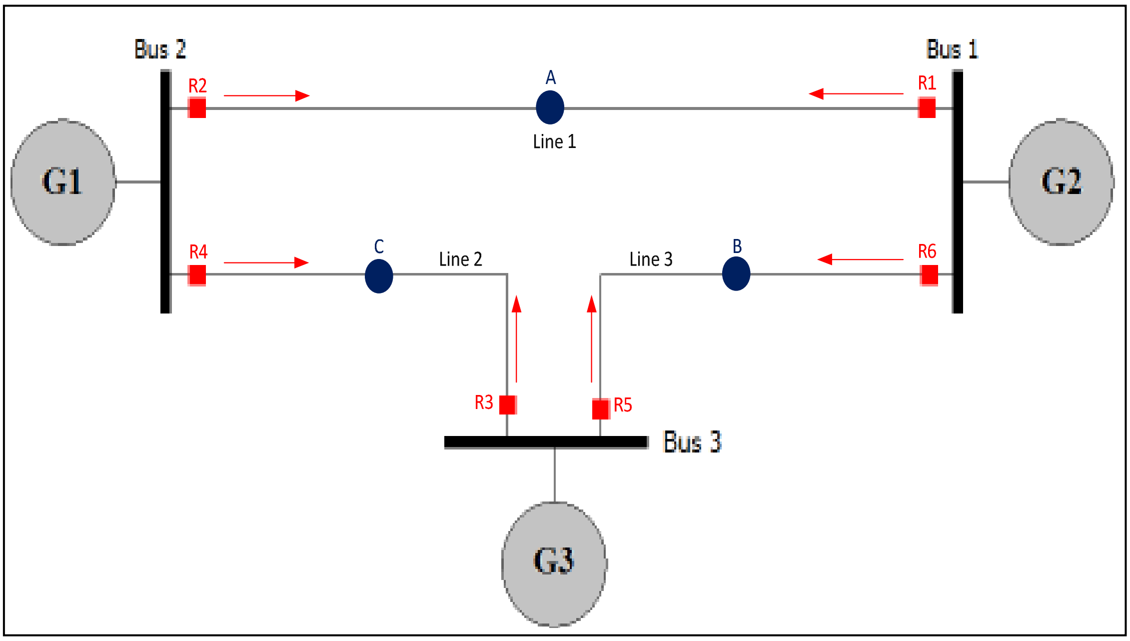
**Table E.2**

*Current transformer ratio for primary relays in IEEE 3-bus network*

| Relay Number | CT ratio |
|---|---|
| 1, 4 | 300/5 |
| 2, 3, 5 | 200/5 |
| 6 | 400/5 |

**Figure E.1**

*IEEE 3-bus network single-line diagram*



**Test System II: IEEE 6-bus**

**Table E.3**

*Three-phase short circuit current of IEEE 6-bus network*

| Primary Relay | Short circuit Current (kA) | Backup Relay | Short circuit Current (kA) |
|---|---|---|---|
| 1 | 18.172 | 13 | 0.6010 |
| 2 | 4.8030 | 3 | 1.3650 |
| 3 | 30.547 | 4 | 0.5528 |
| 4 | 5.1860 | 12 | 3.4220 |
| 4 | 5.1860 | 14 | 1.7640 |
| 5 | 2.8380 | 11 | 1.0740 |
| 5 | 2.8380 | 14 | 1.7640 |
| 6 | 18.338 | 8 | 0.7670 |
| 7 | 4.4960 | 11 | 1.0740 |
| 7 | 4.4960 | 12 | 3.4220 |
| 8 | 2.3510 | 2 | 0.8690 |
| 8 | 2.3510 | 7 | 1.4830 |
| 9 | 6.0720 | 1 | 4.5890 |
| 9 | 6.0720 | 7 | 1.4830 |
| 10 | 4.0770 | 9 | 0.6390 |
| 11 | 30.939 | 10 | 0.9455 |
| 12 | 17.705 | 6 | 0.8610 |
| 13 | 17.821 | 5 | 0.9770 |
| 14 | 5.4570 | 1 | 4.5890 |
| 14 | 5.4570 | 2 | 0.8680 |

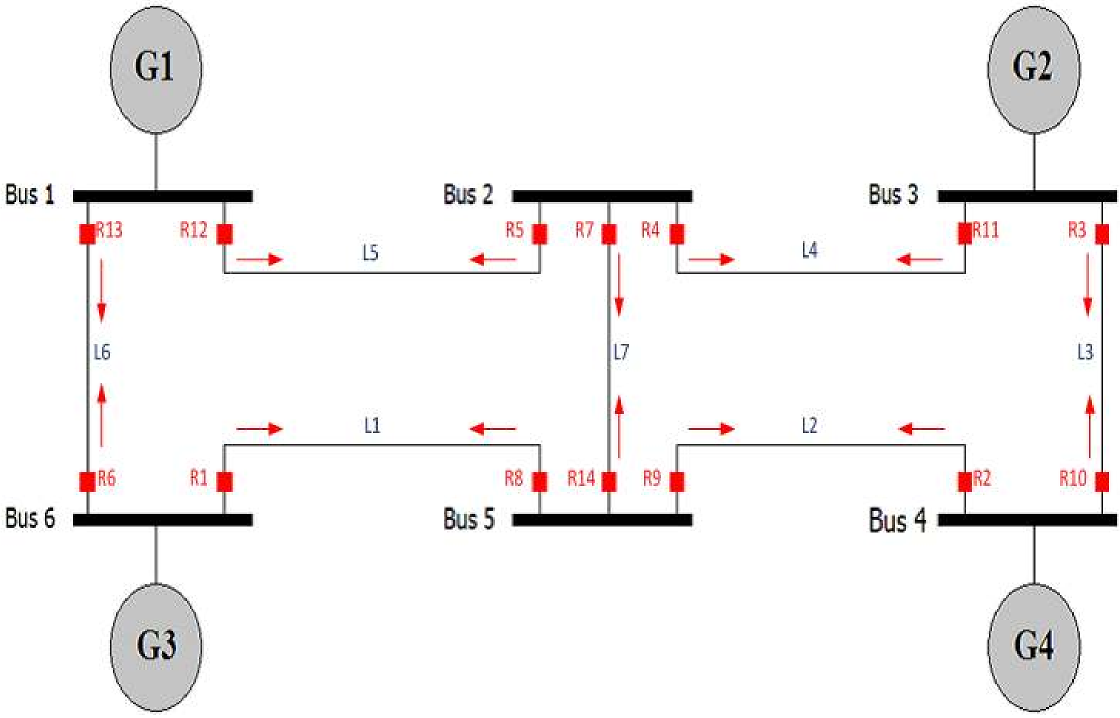
**Table E.4**

*Current transformer ratio for primary relays in IEEE 6-bus network*

| Relay Number | CT ratio |
|---|---|
| 1, 6, 13 | 1200/5 |
| 2, 3, 4, 5, 7, 8, 9, 11, 12, 14 | 800/5 |
| 10 | 600/5 |

**Figure E.2**

*IEEE 6-bus network single-line diagram*



**Test System III: IEEE 9-bus**

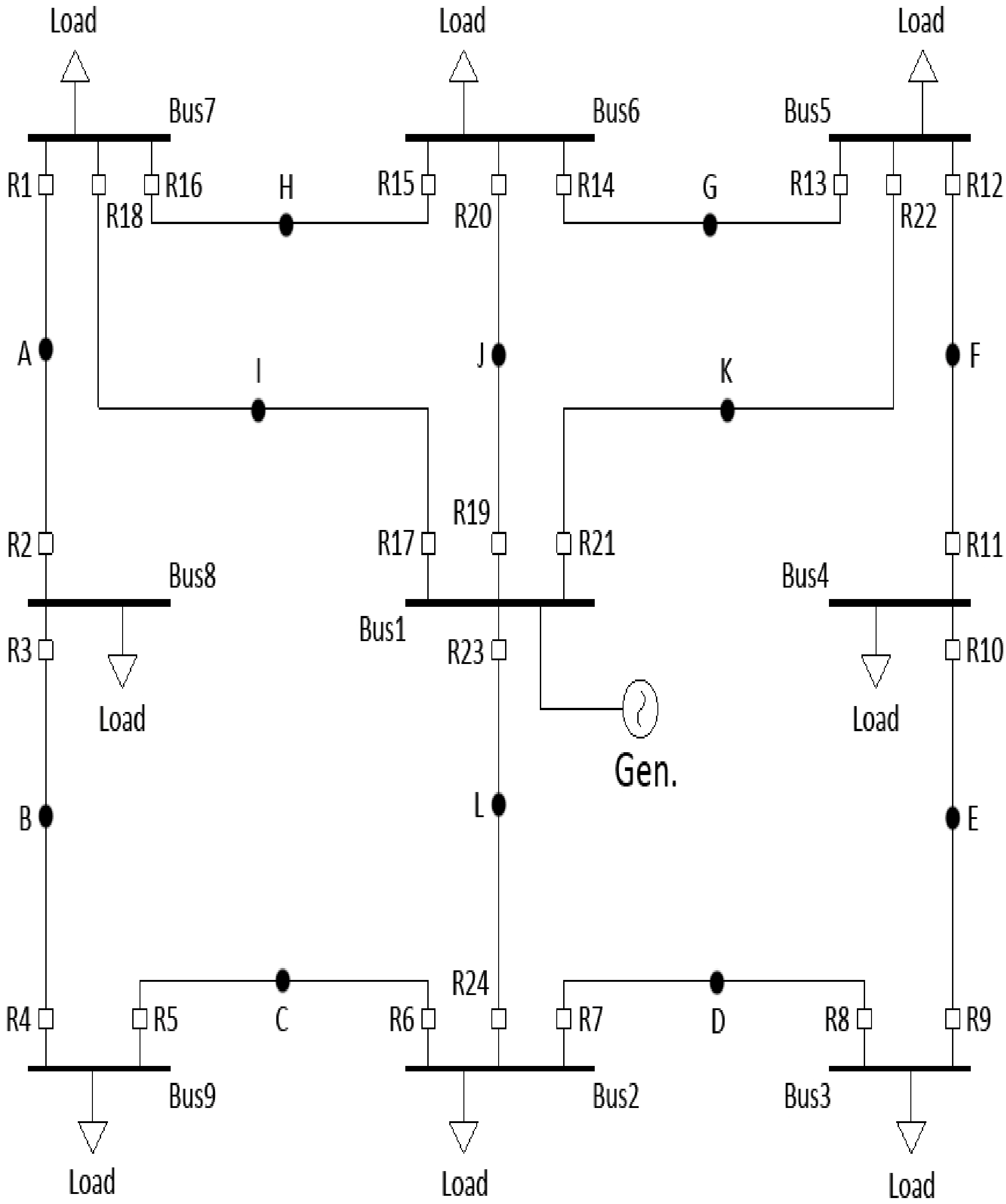
*Table E.5*

*Three-phase short circuit current of IEEE 9-bus network*

| Primary Relay | Short circuit Current (A) | Backup Relay | Short circuit Current (A) |
|---|---|---|---|
| 1 | 4863.6 | 15 | 1168.3 |
| 1 | 4863.6 | 17 | 1293.9 |
| 2 | 1634.4 | 4 | 1044.2 |
| 3 | 2811.4 | 1 | 1361.6 |
| 4 | 2610.5 | 6 | 1226.0 |
| 5 | 1778.0 | 3 | 1124.4 |
| 6 | 4378.5 | 8 | 711.20 |
| 6 | 4378.5 | 23 | 1345.5 |
| 7 | 4378.5 | 5 | 711.20 |
| 7 | 4378.5 | 23 | 1345.5 |
| 8 | 1778.0 | 10 | 1124.4 |
| 9 | 2610.5 | 7 | 1226.0 |
| 10 | 2811.4 | 12 | 787.20 |
| 11 | 1634.4 | 9 | 1044.2 |
| 12 | 2811.4 | 14 | 1168.2 |
| 12 | 2811.4 | 21 | 1293.9 |
| 13 | 3684.5 | 11 | 653.60 |
| 13 | 3684.5 | 21 | 1293.9 |
| 14 | 4172.5 | 16 | 1031.7 |
| 14 | 4172.5 | 19 | 1264.1 |
| 15 | 4172.5 | 13 | 1031.7 |
| 15 | 4172.5 | 19 | 1264.1 |
| 16 | 3684.5 | 2 | 653.60 |
| 16 | 3684.5 | 17 | 1293.9 |
| 17 | 7611.2 | - | 0 |
| 18 | 2271.7 | 2 | 653.60 |
| 18 | 2271.7 | 15 | 1168.3 |
| 19 | 7435.8 | - | 0 |
| 20 | 2624.2 | 13 | 1031.7 |
| 20 | 2624.2 | 16 | 1031.7 |
| 21 | 7611.2 | - | 0 |
| 22 | 2271.7 | 11 | 653.60 |
| 22 | 2271.7 | 14 | 1168.3 |
| 23 | 7914.7 | - | 0 |
| 24 | 1665.5 | 5 | 711.20 |
| 24 | 1665.5 | 8 | 711.20 |

**Figure E.3**

*IEEE 9-bus network single-line diagram*



**Test System IV: IEEE 15-bus**

**Table E.6**

*Three-phase short circuit current of IEEE 15-bus network*

| Primary Relay | Short circuit Current (A) | Backup Relay | Short circuit Current (A) | Primary Relay | Short circuit Current (A) | Backup Relay | Short circuit Current (A) |
|---|---|---|---|---|---|---|---|
| 1 | 3621 | 6 | 1233 | 20 | 7662 | 30 | 681 |
| 2 | 4597 | 4 | 1477 | 21 | 8384 | 17 | 599 |
| 2 | 4597 | 16 | 743 | 21 | 8384 | 19 | 1372 |
| 3 | 3984 | 1 | 853 | 21 | 8384 | 30 | 681 |
| 3 | 3984 | 16 | 743 | 22 | 1950 | 23 | 979 |
| 4 | 4382 | 7 | 1111 | 22 | 1950 | 34 | 970 |
| 4 | 4382 | 12 | 1463 | 23 | 4910 | 11 | 1475 |
| 4 | 4382 | 20 | 1808 | 23 | 4910 | 13 | 1503 |
| 5 | 3319 | 2 | 922 | 24 | 2296 | 21 | 1326 |
| 6 | 2647 | 8 | 1548 | 24 | 2296 | 34 | 970 |
| 6 | 2647 | 10 | 1100 | 25 | 2289 | 15 | 969 |
| 7 | 2497 | 5 | 1397 | 25 | 2289 | 18 | 1320 |
| 7 | 2497 | 10 | 1100 | 26 | 2300 | 28 | 1192 |
| 8 | 4695 | 3 | 1424 | 26 | 2300 | 36 | 1109 |
| 8 | 4695 | 12 | 1463 | 27 | 2011 | 25 | 903 |
| 8 | 4695 | 20 | 1808 | 27 | 2011 | 36 | 1109 |
| 9 | 2943 | 5 | 1397 | 28 | 2525 | 29 | 1828 |
| 9 | 2943 | 8 | 1548 | 28 | 2525 | 32 | 697 |
| 10 | 3568 | 14 | 1175 | 29 | 8346 | 17 | 599 |
| 11 | 4342 | 3 | 1424 | 29 | 8346 | 19 | 1372 |
| 11 | 4342 | 7 | 1111 | 29 | 8346 | 22 | 642 |
| 11 | 4342 | 20 | 1808 | 30 | 1736 | 27 | 1039 |
| 12 | 4195 | 13 | 1503 | 30 | 1736 | 32 | 697 |
| 12 | 4195 | 24 | 753 | 31 | 2867 | 27 | 1039 |
| 13 | 3402 | 9 | 1009 | 31 | 2867 | 29 | 1828 |
| 14 | 4606 | 11 | 1475 | 32 | 2069 | 33 | 1162 |
| 14 | 4606 | 24 | 753 | 32 | 2069 | 42 | 907 |
| 15 | 4712 | 1 | 853 | 33 | 2305 | 21 | 1326 |
| 15 | 4712 | 4 | 1477 | 33 | 2305 | 23 | 979 |
| 16 | 2225 | 18 | 1320 | 34 | 1715 | 31 | 809 |
| 16 | 2225 | 26 | 905 | 34 | 1715 | 42 | 907 |
| 17 | 1875 | 15 | 969 | 35 | 2095 | 25 | 903 |
| 17 | 1875 | 26 | 905 | 35 | 2095 | 28 | 1192 |
| 18 | 8426 | 19 | 1372 | 36 | 3283 | 38 | 882 |
| 18 | 8426 | 22 | 642 | 37 | 3301 | 35 | 910 |
| 18 | 8426 | 30 | 681 | 38 | 1403 | 40 | 1403 |
| 19 | 3998 | 3 | 1424 | 39 | 1434 | 37 | 1434 |
| 19 | 3998 | 7 | 1111 | 40 | 3140 | 41 | 1434 |
| 19 | 3998 | 12 | 1463 | 41 | 1971 | 31 | 809 |
| 20 | 7662 | 17 | 599 | 41 | 1971 | 33 | 1162 |
| 20 | 7662 | 22 | 642 | 42 | 3295 | 39 | 896 |

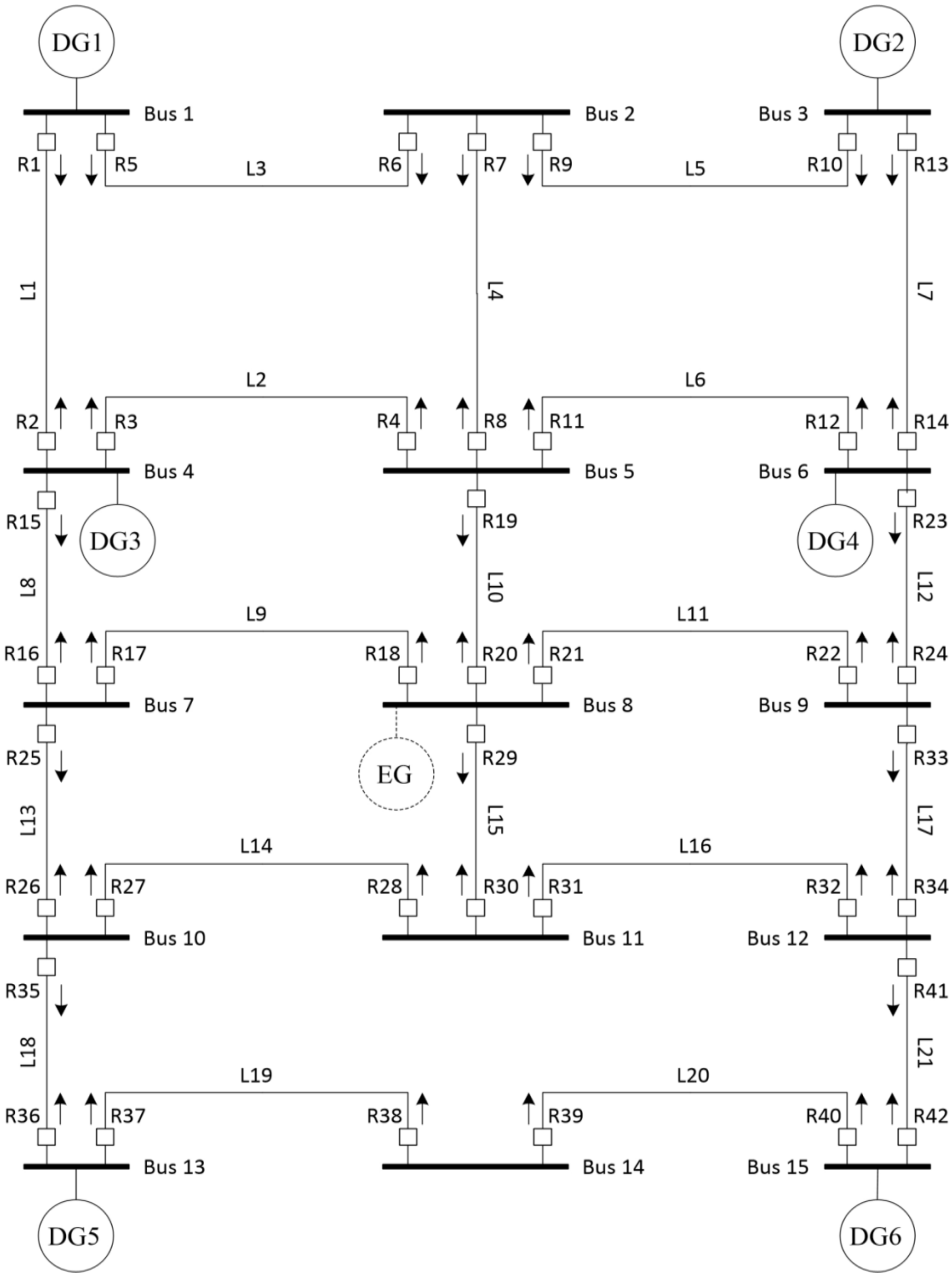
**Table E.7**

*Current transformer ratio for primary relays in IEEE 15-bus network*

| Relay Number | CT ratio |
|---|---|
| 17, 22, 30, 34, 38, 39, 41 | 400/5 |
| 6, 7, 9, 16, 24, 25, 26, 27, 28, 31, 32, 33,35 | 600/5 |
| 1, 3, 5, 10, 13, 19, 36, 37, 40, 42 | 800/5 |
| 2, 4, 8, 11, 12, 14, 15, 23 | 1200/5 |
| 18, 20, 21, 29 | 1600/5 |

**Figure E.4**

*IEEE 15-bus network single-line diagram*



# Appendix F

# Results

**IEEE 6-bus Linear Programming Formulation**

**Table F.1**

*PS values for relays in IEEE 6-bus network*

| Relay Number | PS | Relay Number | PS |
|---|---|---|---|
| 1 | 0.8 | 8 | 0.8 |
| 2 | 0.8 | 9 | 0.5 |
| 3 | 1.0 | 10 | 1.0 |
| 4 | 0.5 | 11 | 1.0 |
| 5 | 0.5 | 12 | 1.5 |
| 6 | 0.5 | 13 | 0.5 |
| 7 | 1.0 | 14 | 1.0 |

**Table F.2**

*LP-based relay settings for the IEEE 6-bus network*

| TMS | TLBO [24] | PSO-DE [92] | IA-PSO [113] | FA [35] | IFA [35] | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|---|
| R1 | 0.3780 | 0.4064 | 0.2602 | 0.1002 | 0.1000 | 0.281092 | 0.237645 | 0.237660 |
| R2 | 0.3443 | 0.7506 | 0.4739 | 0.1002 | 0.1000 | 0.183928 | 0.141543 | 0.141515 |
| R3 | 0.2553 | 0.3872 | 0.2406 | 0.1006 | 0.1296 | 0.342781 | 0.145152 | 0.145036 |
| R4 | 0.3346 | 0.4031 | 0.2711 | 0.1102 | 0.1050 | 0.178586 | 0.107978 | 0.108029 |
| R5 | 0.1005 | 0.2005 | 0.1268 | 0.1000 | 0.1007 | 0.144307 | 0.136076 | 0.136054 |
| R6 | 0.2376 | 0.2011 | 0.1264 | 0.4070 | 0.3880 | 0.142615 | 0.142682 | 0.142615 |
| R7 | 0.3000 | 0.2003 | 0.1265 | 0.1092 | 0.1016 | 0.141982 | 0.142060 | 0.141982 |
| R8 | 0.4720 | 0.2133 | 0.1265 | 0.1000 | 0.1000 | 0.101237 | 0.101296 | 0.101237 |
| R9 | 0.0414 | 0.2006 | 0.1268 | 0.1175 | 0.1128 | 0.133389 | 0.125504 | 0.125525 |
| R10 | 0.3323 | 0.2265 | 0.1424 | 0.2860 | 0.1001 | 0.111931 | 0.111617 | 0.111619 |
| R11 | 0.2518 | 0.2610 | 0.1647 | 0.1439 | 0.1143 | 0.135528 | 0.135385 | 0.135377 |
| R12 | 0.2704 | 0.2039 | 0.1401 | 0.3404 | 0.2138 | 0.190353 | 0.190452 | 0.190353 |
| R13 | 0.1735 | 0.2002 | 0.1265 | 0.1063 | 0.1899 | 0.144114 | 0.128572 | 0.128488 |
| R14 | 0.2817 | 0.2837 | 0.1170 | 0.4070 | 0.2881 | 0.171252 | 0.160715 | 0.160723 |
| Fitness | 23.787 | 9.2671 | 8.1245 | 7.6866 | 6.4040 | 3.87061 | 3.29554 | 3.29480 |

**Table F.3**

*Comparison of the proposed methods' percentage improvement and the overall net gain in time over the literature's algorithms*

| Method | $\sum \Delta(t)$ (sec) | % Improvement | Method | $\sum \Delta(t)$ (sec) | % Improvement |
|---|---|---|---|---|---|
| MFA/TLBO | 19.9164 | 83.728 | FAGA/TLBO | 20.4922 | 85.149 |
| MFA/PSO-DE | 5.39649 | 58.233 | FAGA/PSO-DE | 5.97230 | 64.446 |
| MFA/ IA-PSO | 4.25389 | 52.359 | FAGA/ IA-PSO | 4.82970 | 59.446 |
| MFA/ FA | 3.81599 | 49.645 | FAGA/ FA | 4.39180 | 57.136 |
| MFA/ IFA | 2.53339 | 39.559 | FAGA/ IFA | 3.10920 | 48.551 |
| MFA/GA | - | - | FAGA/GA | 0.00074 | 0.0225 |

**Table F.4**

*CTI using the LP formulation for the IEEE 6-bus network*

| P/R | MFA | GA | FAGA |
|---|---|---|---|
| | CTI | CTI | CTI |
| 1 | 0.20481 | 0.20038 | 0.20045 |
| 2 | 0.75308 | 0.20013 | 0.20034 |
| 3 | 0.20096 | 0.20003 | 0.20028 |
| 4 | 0.20074 | 0.31476 | 0.31503 |
| 5 | 0.19955 | 0.28391 | 0.28374 |
| 6 | 0.21762 | 0.23064 | 0.23084 |
| 7 | 0.21437 | 0.20000 | 0.20004 |
| 8 | 0.20069 | 0.20050 | 0.20035 |
| 9 | 0.20195 | 0.20033 | 0.20026 |
| 10 | 0.20000 | 0.20047 | 0.20075 |
| 11 | 0.42290 | 0.27130 | 0.27113 |
| 12 | 0.20000 | 0.20000 | 0.20000 |
| 13 | 0.39363 | 0.31339 | 0.31337 |
| 14 | 0.22975 | 0.24197 | 0.24204 |
| 15 | 0.22601 | 0.20031 | 0.20044 |
| 16 | 0.20087 | 0.20027 | 0.20035 |
| 17 | 0.20050 | 0.20048 | 0.20035 |
| 18 | 0.20043 | 0.20039 | 0.20010 |
| 19 | 0.27309 | 0.20010 | 0.20020 |
| 20 | 0.33201 | 0.20049 | 0.20016 |

**IEEE 6-bus Non Linear Programming Formulation**

**Table F.5**

*NLP-based relay settings for the IEEE 6-bus network*

| Variables | MFA | GA | FAGA |
|---|---|---|---|
| TMS1 | 0.436650 | 0.287456 | 0.249768 |
| TMS2 | 0.100016 | 0.185867 | 0.100016 |
| TMS3 | 0.121972 | 0.175585 | 0.101220 |
| TMS4 | 0.100000 | 0.146315 | 0.100000 |
| TMS5 | 0.100001 | 0.139980 | 0.100001 |
| TMS6 | 0.100000 | 0.100125 | 0.100000 |
| TMS7 | 0.137568 | 0.193363 | 0.136347 |
| TMS8 | 0.152850 | 0.158478 | 0.151751 |
| TMS9 | 0.113350 | 0.149016 | 0.100655 |
| TMS10 | 0.178494 | 0.200589 | 0.176909 |
| TMS11 | 0.100000 | 0.125244 | 0.100000 |
| TMS12 | 0.272713 | 0.311442 | 0.271248 |
| TMS13 | 0.100007 | 0.136331 | 0.100007 |
| TMS14 | 0.122226 | 0.200200 | 0.117578 |
| PS1 | 1.079420 | 0.501935 | 0.500038 |
| PS2 | 1.755140 | 0.500968 | 1.400890 |
| PS3 | 1.787890 | 0.793011 | 1.633960 |
| PS4 | 1.458140 | 0.501100 | 0.696583 |
| PS5 | 2.319870 | 0.500247 | 0.823288 |
| PS6 | 2.077760 | 1.015010 | 0.948732 |
| PS7 | 1.709690 | 0.727959 | 1.469700 |
| PS8 | 0.820459 | 0.500476 | 0.527368 |
| PS9 | 1.197200 | 0.500027 | 0.890075 |
| PS10 | 0.574520 | 0.500830 | 0.555721 |
| PS11 | 1.940750 | 1.428750 | 1.755200 |
| PS12 | 0.678410 | 0.502007 | 0.606144 |
| PS13 | 1.819770 | 0.500759 | 0.682573 |
| PS14 | 2.298170 | 0.592759 | 1.621050 |
| Fitness | 4.04849 | 3.84454 | 3.22831 |

**Table F.6**

*CTI using the NLP formulation for the IEEE 6-bus network*

| P/R | MFA | GA | FAGA |
|---|---|---|---|
| | CTI | CTI | CTI |
| 1 | 1.50040 | 0.20206 | 0.20051 |
| 2 | 0.29804 | 0.20011 | 0.20015 |
| 3 | 0.51849 | 0.20118 | 0.20004 |
| 4 | 0.31570 | 0.32398 | 0.33869 |
| 5 | 0.31853 | 0.23006 | 0.24667 |
| 6 | 0.22010 | 0.29435 | 0.29378 |
| 7 | 0.20006 | 0.20068 | 0.20095 |
| 8 | 0.20016 | 0.20140 | 0.20000 |
| 9 | 0.22295 | 0.20213 | 0.20087 |
| 10 | 0.20008 | 0.20240 | 0.20007 |
| 11 | 0.25300 | 0.21605 | 0.20138 |
| 12 | 0.20000 | 0.20132 | 0.20003 |
| 13 | 0.81153 | 0.30225 | 0.28175 |
| 14 | 0.33840 | 0.28794 | 0.32798 |
| 15 | 0.38422 | 0.20121 | 0.20002 |
| 16 | 0.20000 | 0.20000 | 0.20009 |
| 17 | 0.95586 | 0.20355 | 0.20941 |
| 18 | 0.53451 | 0.20041 | 0.20004 |
| 19 | 0.72445 | 0.20089 | 0.20000 |
| 20 | 0.30460 | 0.20131 | 0.24756 |

**Figure F.1**

*Total operation time compared to the literature for the proposed methods*

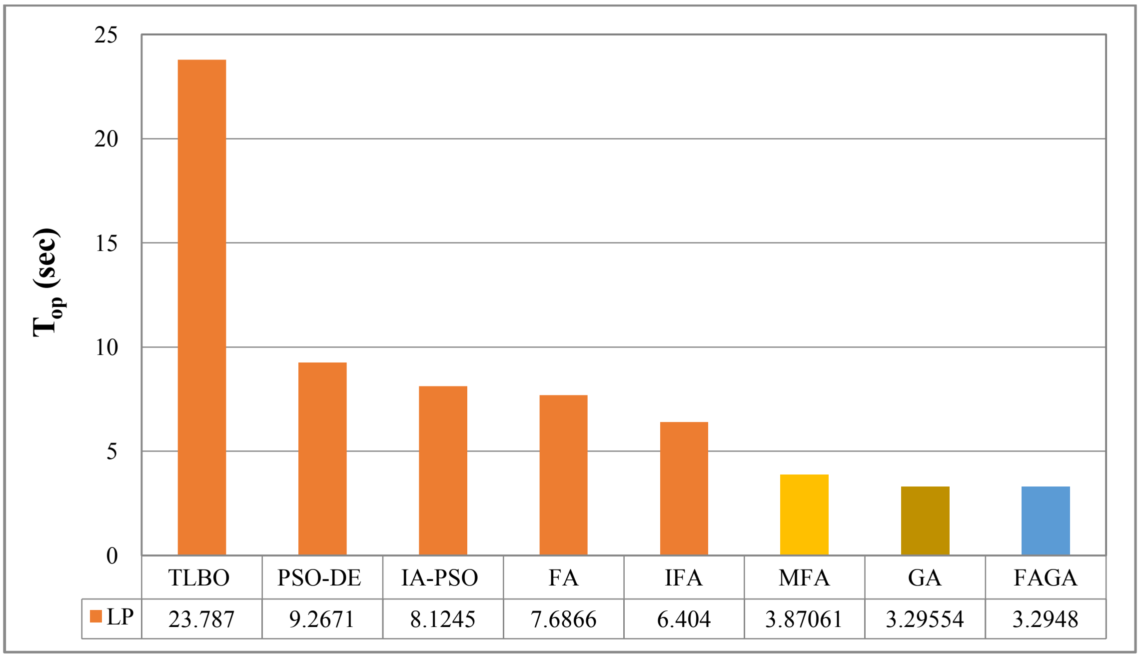


**Figure F.2**

*Percentage improvement of the proposed methods compared to other algorithms in the literature for IEEE 3-bus network in terms of the net relay operational time*

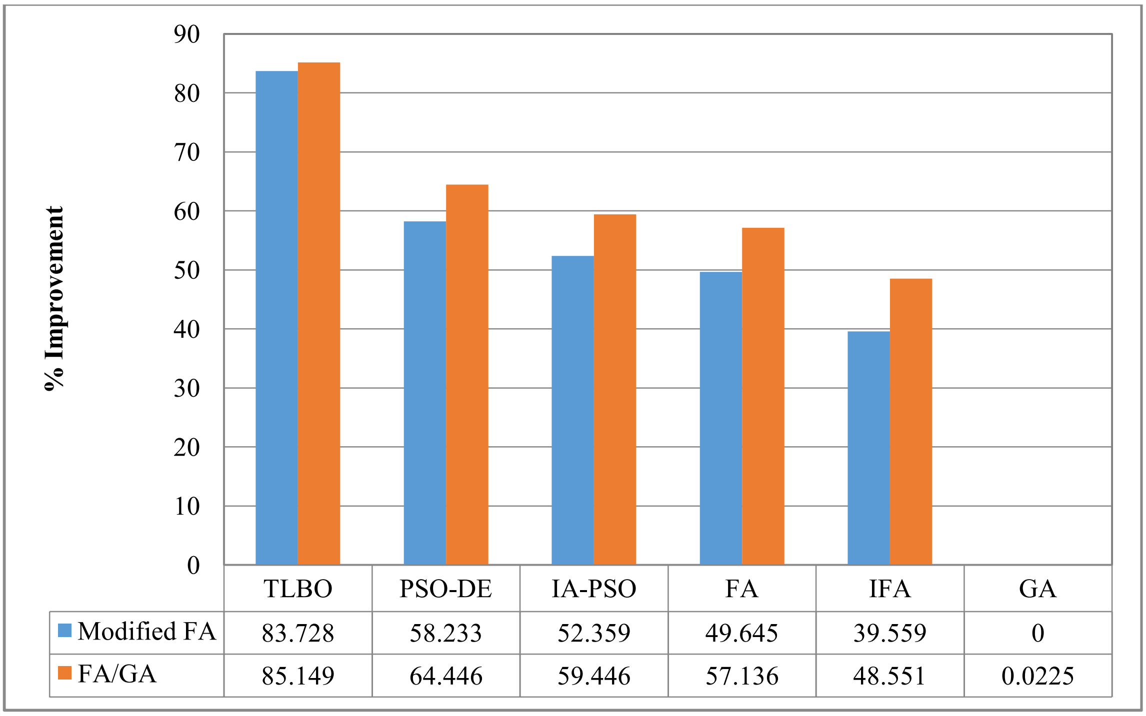
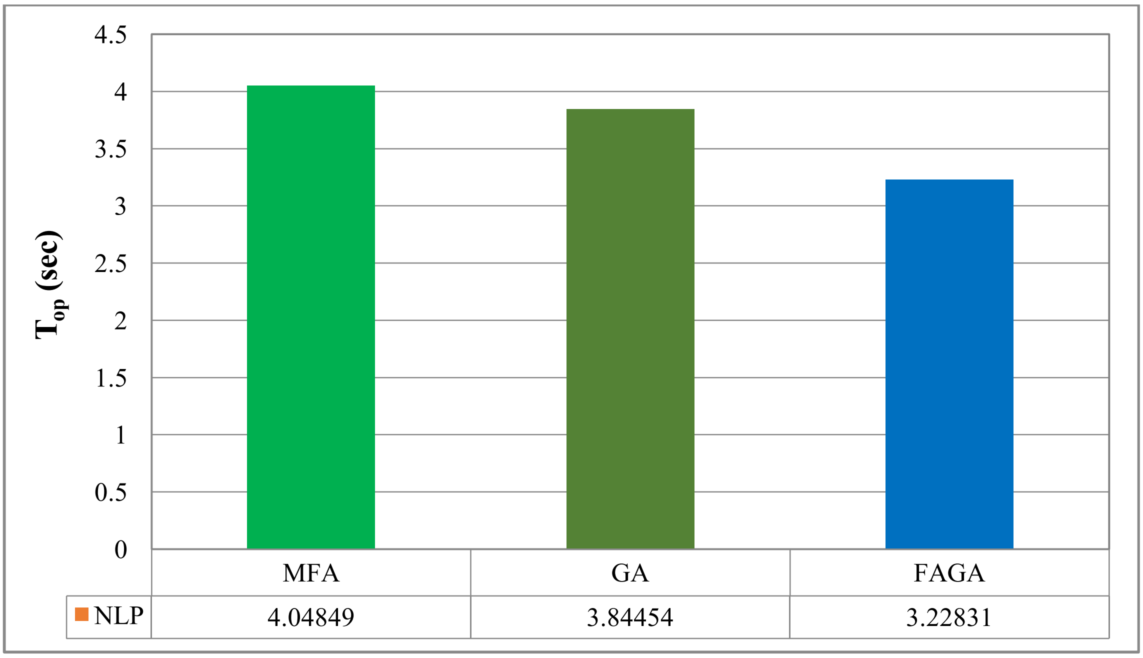



**Figure F.3**

*Total operating time of the proposed methods.*



**IEEE 9-bus Non Linear Programming Formulation**

**Table F.7**

*NLP-based relay settings for the IEEE 9-bus network*

| Variables | Seeker [114] | FA [35] | IFA [35] | WOA [35] | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|
| TMS1 | 0.2662 | 1.0850 | 0.9788 | 0.1039 | 0.100000 | 0.100045 | 0.100000 |
| TMS2 | 0.2076 | 1.0654 | 0.7945 | 0.5934 | 0.100000 | 0.100024 | 0.100000 |
| TMS3 | 0.2928 | 0.5560 | 0.1309 | 0.6080 | 0.121327 | 0.100000 | 0.111683 |
| TMS4 | 0.3192 | 0.4492 | 0.3740 | 0.1000 | 0.100006 | 0.100072 | 0.100000 |
| TMS5 | 0.2879 | 0.7472 | 0.3880 | 0.1000 | 0.100000 | 0.100015 | 0.100000 |
| TMS6 | 0.3677 | 1.0764 | 0.6056 | 1.1000 | 0.123330 | 0.100000 | 0.112346 |
| TMS7 | 0.3006 | 0.9764 | 0.6240 | 0.3927 | 0.100022 | 0.100000 | 0.100022 |
| TMS8 | 0.2905 | 1.0472 | 1.0285 | 1.1000 | 0.100000 | 0.100083 | 0.100000 |
| TMS9 | 0.2476 | 1.0492 | 0.5377 | 0.1000 | 0.100000 | 0.117236 | 0.100000 |
| TMS10 | 0.2480 | 0.8557 | 0.7623 | 0.1000 | 0.100000 | 0.119556 | 0.100000 |
| TMS11 | 0.2578 | 0.7305 | 0.2139 | 1.1000 | 0.100035 | 0.100000 | 0.100035 |
| TMS12 | 0.3665 | 0.9802 | 0.5964 | 0.2313 | 0.100100 | 0.100024 | 0.100100 |
| TMS13 | 0.2581 | 1.0492 | 0.9327 | 0.5111 | 0.100000 | 0.100282 | 0.100000 |
| TMS14 | 0.3117 | 1.0637 | 0.7761 | 0.1000 | 0.100026 | 0.100103 | 0.100026 |
| TMS15 | 0.2921 | 1.0908 | 0.6309 | 0.1000 | 0.428972 | 0.101203 | 0.114164 |
| TMS16 | 0.3633 | 1.0593 | 1.0295 | 0.8753 | 0.100138 | 0.100041 | 0.100016 |
| TMS17 | 0.2560 | 0.9420 | 0.2740 | 0.1005 | 0.375384 | 0.100000 | 0.111377 |
| TMS18 | 0.1038 | 1.0295 | 0.6019 | 0.1005 | 0.100000 | 0.100024 | 0.100000 |
| TMS19 | 0.2589 | 1.0572 | 0.7807 | 0.1121 | 0.130127 | 0.115283 | 0.100098 |
| TMS20 | 0.1002 | 0.3245 | 0.2164 | 0.2180 | 0.100114 | 0.100000 | 0.100114 |
| TMS21 | 0.2758 | 0.5918 | 0.3072 | 0.1000 | 0.116052 | 0.100090 | 0.100061 |
| TMS22 | 0.1010 | 0.6747 | 0.4921 | 0.1000 | 0.100000 | 0.100000 | 0.100000 |
| TMS23 | 0.1757 | 0.6609 | 0.1011 | 0.1005 | 0.100036 | 0.113113 | 0.100036 |
| TMS24 | 0.1014 | 0.9041 | 0.4305 | 0.1000 | 0.100000 | 0.100046 | 0.100000 |
| PS1 | 1.2732 | 1.8150 | 1.6079 | 0.5196 | 1.480550 | 0.713501 | 0.749105 |
| PS2 | 1.5200 | 1.2988 | 0.3692 | 1.3962 | 0.542203 | 0.500025 | 0.500089 |
| PS3 | 1.1975 | 1.4980 | 0.9686 | 0.6714 | 0.5827590 | 0.639849 | 0.556856 |
| PS4 | 0.6701 | 1.3920 | 0.3262 | 0.5000 | 0.8656400 | 0.667917 | 0.619558 |
| PS5 | 1.0785 | 0.9480 | 0.4523 | 0.5000 | 0.7030500 | 0.500011 | 0.506492 |
| PS6 | 0.6311 | 1.6430 | 1.5864 | 2.0000 | 0.5672920 | 0.696574 | 0.555085 |
| PS7 | 0.9637 | 1.6430 | 1.3431 | 0.7141 | 0.8748260 | 0.668990 | 0.615549 |
| PS8 | 1.1393 | 0.9480 | 0.2088 | 2.0000 | 0.5882030 | 0.500019 | 0.500068 |
| PS9 | 1.1994 | 1.3920 | 0.4618 | 0.5000 | 0.8313440 | 0.500061 | 0.657638 |
| PS10 | 1.7451 | 1.4980 | 0.8566 | 0.5000 | 1.0481100 | 0.502563 | 0.640949 |
| PS11 | 0.8454 | 1.1369 | 1.1585 | 2.0000 | 0.9184340 | 0.500000 | 0.553641 |
| PS12 | 0.6461 | 1.8150 | 1.7203 | 0.8336 | 0.6561500 | 0.500018 | 0.500022 |
| PS13 | 0.9784 | 1.3740 | 0.9274 | 0.5283 | 1.5035700 | 0.503662 | 0.519555 |

| Variables | Seeker [114] | FA [35] | IFA [35] | WOA [35] | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|
| PS14 | 0.8860 | 1.5560 | 0.6999 | 0.5000 | 1.9258400 | 0.785659 | 0.603911 |
| PS15 | 0.8993 | 1.5560 | 0.5456 | 0.5000 | 0.5042720 | 0.594298 | 0.500122 |
| PS16 | 0.5004 | 0.9639 | 0.9873 | 1.2390 | 1.3279600 | 0.507543 | 0.508474 |
| PS17 | 0.9197 | 1.7200 | 1.3869 | 0.5129 | 0.5009380 | 0.982412 | 0.500328 |
| PS18 | 0.5003 | 1.6347 | 1.9435 | 0.5028 | 0.6570340 | 0.500000 | 0.500284 |
| PS19 | 0.7629 | 1.6800 | 1.2390 | 0.5000 | 1.2197700 | 0.500000 | 0.628484 |
| PS20 | 0.5041 | 0.8006 | 0.7110 | 1.6530 | 0.6508340 | 0.500000 | 0.500077 |
| PS21 | 0.8902 | 1.7200 | 1.6203 | 0.5000 | 1.2047200 | 0.622735 | 0.763314 |
| PS22 | 0.5008 | 0.7000 | 0.5859 | 0.5000 | 0.9303220 | 0.500000 | 0.500055 |
| PS23 | 1.5724 | 1.7900 | 1.4038 | 0.5025 | 1.1970700 | 0.512695 | 0.635455 |
| PS24 | 0.5017 | 0.7441 | 0.7467 | 0.5000 | 0.9271820 | 0.500022 | 0.500281 |
| Fitness | 14.2338 | 14.2216 | 13.3409 | 13.7000 | 10.23700 | 7.08666 | 7.03106 |

**Table F.8**

*Comparison of the proposed methods' percentage improvement and the overall net gain in time over the literature's algorithms*

| Method | $\sum \Delta(t)$ (sec) | % Improvement | Method | $\sum \Delta(t)$ (sec) | % Improvement |
|---|---|---|---|---|---|
| MFA/ TLBO [115] | 72.6642 | 87.6516 | FAGA/TLBO [115] | 75.87014 | 91.5188 |
| MFA/ IDE [115] | 46.4101 | 81.9285 | FAGA/ IDE [115] | 49.61604 | 87.5879 |
| MFA/BBO [8] | 18.5978 | 64.4978 | FAGA/BBO [8] | 21.80374 | 75.6161 |
| MFA/ FA | 3.9968 | 28.0796 | FAGA/ FA | 7.20274 | 50.6031 |
| MFA/ IFA | 3.9846 | 28.0179 | FAGA/ IFA | 7.19054 | 50.5607 |
| MFA/ WOA | 3.1039 | 22.6562 | FAGA/ WOS | 6.30984 | 46.5722 |
| MFA/GA | - | - | FAGA/GA | 0.05560 | 0.78457 |

**Table F.9**

*CTI using the NLP formulation for the IEEE 9-bus network*

| P/R | MFA | GA | FAGA |
|---|---|---|---|
| | CTI | CTI | CTI |
| 1 | 1.563200 | 0.24947 | 0.24435 |
| 2 | 1.207000 | 0.45453 | 0.20059 |
| 3 | 0.406350 | 0.24184 | 0.20319 |
| 4 | 0.777460 | 0.20103 | 0.20503 |
| 5 | 0.197750 | 0.21582 | 0.20009 |
| 6 | 0.194270 | 0.20000 | 0.20007 |
| 7 | 0.479920 | 0.39416 | 0.38535 |
| 8 | 0.550260 | 0.20010 | 0.20090 |
| 9 | 0.691380 | 0.39818 | 0.41417 |
| 10 | 0.559510 | 0.20473 | 0.22143 |
| 11 | 0.527580 | 0.20000 | 0.20082 |
| 12 | 0.361250 | 0.22789 | 0.20191 |
| 13 | 0.385170 | 0.26540 | 0.28854 |
| 14 | 0.207930 | 0.20006 | 0.21138 |
| 15 | 3.299800 | 0.35356 | 0.22792 |
| 16 | 0.735760 | 0.20282 | 0.28412 |
| 17 | - | - | - |
| 18 | 1.544000 | 0.46712 | 0.55129 |
| 19 | - | - | - |
| 20 | 0.620760 | 0.23049 | 0.30972 |
| 21 | - | - | - |
| 22 | 1.113300 | 0.20271 | 0.23325 |
| 23 | - | - | - |
| 24 | 0.770660 | 0.20048 | 0.23671 |
| 25 | 1.172100 | 0.22988 | 0.22458 |
| 26 | 0.20162 | 0.22884 | 0.22039 |
| 27 | 0.38757 | 0.46743 | 0.46660 |
| 28 | 1.16970 | 0.46100 | 0.21174 |
| 29 | 0.43498 | 0.41171 | 0.41121 |
| 30 | 1.57340 | 0.20021 | 0.20011 |
| 31 | 1.88400 | 0.20007 | 0.20945 |
| 32 | 1.25620 | 0.20126 | 0.20181 |
| 33 | 1.54420 | 0.41149 | 0.49803 |
| 34 | 3.18490 | 0.32560 | 0.20026 |
| 35 | 0.44749 | 0.30093 | 0.30860 |
| 36 | 0.24528 | 0.30154 | 0.30032 |

**Figure F.4**

*Total operation time compared to the literature for the proposed methods*

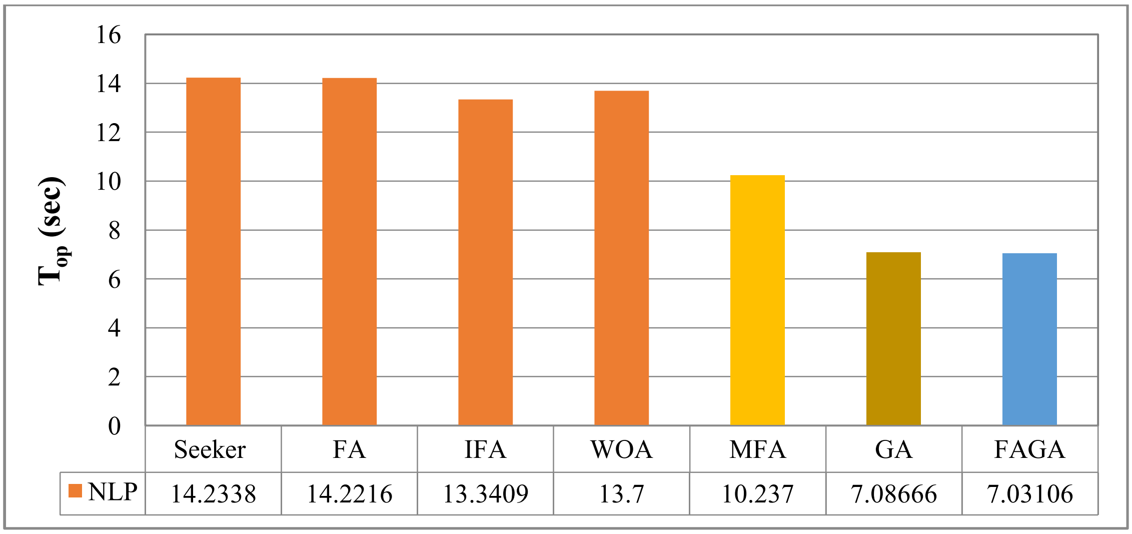
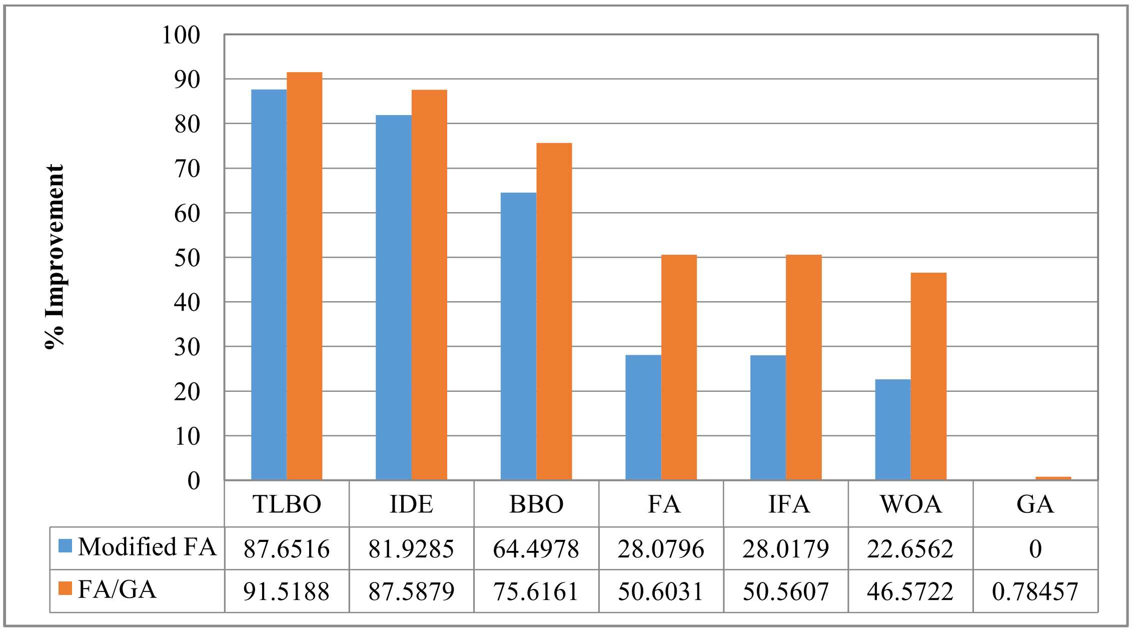



**Figure F.5**

*Percentage improvement of the proposed methods compared to other algorithms in the literature for IEEE 3-bus network in terms of the net relay operational time*



**IEEE 15-bus Non Linear Programming Formulation**

**Table F.10**

*NLP-based relay settings for the IEEE 15-bus network*

| Relay | MFA | | GA | | FAGA | |
|---|---|---|---|---|---|---|
| | TMS | PS | TMS | PS | TMS | PS |
| 1 | 0.100272 | 2.112490 | 0.206152 | 0.500055 | 0.100028 | 2.108580 |
| 2 | 0.199528 | 0.818450 | 0.208066 | 0.500000 | 0.168278 | 0.810638 |
| 3 | 0.148360 | 1.631750 | 0.133555 | 2.047870 | 0.148116 | 1.631510 |
| 4 | 0.102725 | 1.985600 | 0.217709 | 0.500111 | 0.102725 | 1.985600 |
| 5 | 0.132894 | 2.051690 | 0.252685 | 0.678760 | 0.128988 | 2.051690 |
| 6 | 0.143683 | 1.769940 | 0.123010 | 2.298000 | 0.143439 | 1.769940 |
| 7 | 0.126064 | 2.362570 | 0.135935 | 2.056640 | 0.125087 | 2.331320 |
| 8 | 0.147295 | 1.370410 | 0.145139 | 1.463750 | 0.138262 | 1.370410 |
| 9 | 0.157093 | 1.586560 | 0.256192 | 0.643388 | 0.157093 | 1.570940 |
| 10 | 0.216869 | 0.774944 | 0.236010 | 0.500244 | 0.216869 | 0.774944 |
| 11 | 0.160230 | 1.132450 | 0.154077 | 0.958190 | 0.160230 | 1.132450 |
| 12 | 0.100060 | 1.885810 | 0.206159 | 0.633033 | 0.100060 | 1.885810 |
| 13 | 0.170058 | 1.510500 | 0.263739 | 0.522666 | 0.169924 | 1.260500 |
| 14 | 0.145922 | 1.019050 | 0.115466 | 1.368390 | 0.145312 | 1.019050 |
| 15 | 0.118373 | 1.437680 | 0.213140 | 0.500702 | 0.118373 | 1.312190 |
| 16 | 0.133919 | 1.450150 | 0.124083 | 1.439820 | 0.133919 | 1.450150 |
| 17 | 0.190055 | 1.171030 | 0.101080 | 2.292620 | 0.174430 | 1.170910 |
| 18 | 0.179936 | 0.575983 | 0.214490 | 0.504973 | 0.179968 | 0.574035 |
| 19 | 0.154495 | 1.367610 | 0.244176 | 0.511433 | 0.154495 | 1.234020 |
| 20 | 0.165046 | 0.841027 | 0.222023 | 0.501041 | 0.164944 | 0.841021 |
| 21 | 0.107406 | 2.059560 | 0.205402 | 0.500000 | 0.107406 | 1.559560 |
| 22 | 0.205113 | 0.604595 | 0.129066 | 1.799800 | 0.205021 | 0.604586 |
| 23 | 0.145834 | 1.655810 | 0.202590 | 0.506614 | 0.144735 | 1.055440 |
| 24 | 0.114539 | 2.033670 | 0.205760 | 0.649283 | 0.112586 | 2.033670 |
| 25 | 0.166519 | 1.328160 | 0.248675 | 0.657970 | 0.166665 | 1.328170 |
| 26 | 0.120819 | 2.151390 | 0.213332 | 0.501492 | 0.119842 | 2.151390 |
| 27 | 0.151402 | 1.242180 | 0.228699 | 0.738998 | 0.151532 | 1.242250 |
| 28 | 0.151529 | 2.048490 | 0.137597 | 2.485720 | 0.151529 | 2.048490 |
| 29 | 0.136204 | 1.715440 | 0.228716 | 0.500117 | 0.134983 | 1.715440 |
| 30 | 0.126348 | 1.665180 | 0.113577 | 2.245970 | 0.126369 | 1.665180 |
| 31 | 0.100447 | 2.437110 | 0.219824 | 0.780606 | 0.100447 | 2.437110 |
| 32 | 0.100045 | 2.253360 | 0.100000 | 1.977600 | 0.100045 | 2.190860 |
| 33 | 0.197349 | 1.171590 | 0.153101 | 2.022740 | 0.197422 | 1.171600 |
| 34 | 0.211959 | 0.976432 | 0.231846 | 0.913722 | 0.211876 | 0.976428 |

| Relay | MFA | | GA | | FAGA | |
|---|---|---|---|---|---|---|
| | TMS | PS | TMS | PS | TMS | PS |
| 35 | 0.208108 | 0.811549 | 0.201486 | 1.036120 | 0.208439 | 0.811591 |
| 36 | 0.131359 | 1.518780 | 0.219030 | 0.805507 | 0.131493 | 1.518790 |
| 37 | 0.169650 | 1.471440 | 0.271151 | 0.510730 | 0.169830 | 1.471460 |
| 38 | 0.130993 | 2.100210 | 0.141771 | 2.497920 | 0.131124 | 2.100210 |
| 39 | 0.155660 | 1.647920 | 0.171159 | 1.290270 | 0.155806 | 1.647930 |
| 40 | 0.222847 | 0.765282 | 0.211496 | 1.103120 | 0.222801 | 0.765034 |
| 41 | 0.190438 | 1.305190 | 0.214445 | 1.139900 | 0.190462 | 1.305190 |
| 42 | 0.149375 | 1.205710 | 0.128640 | 1.586970 | 0.149451 | 1.205730 |
| Fitness | 16.0694 | | 17.2657 | | 15.7578 | |

**Table F.11**

*Comparison of the results for IEEE 15-bus network with NLP formulation.*

| Algorithm | OF | Net gain | | %Improvement |
|---|---|---|---|---|
| MATLBO [115] | 52.5039 | MFA | 36.4345 | 69.394 |
| | | GA | 35.2385 | 67.116 |
| | | FAGA | 36.7461 | 69.987 |
| PSO [114] | 26.8093 | MFA | 10.7399 | 40.060 |
| | | GA | 9.5436 | 35.598 |
| | | FAGA | 11.0515 | 41.223 |
| Jaya [4] | 23.5579 | MFA | 7.4885 | 31.788 |
| | | GA | 6.2922 | 26.709 |
| | | FAGA | 7.8001 | 33.110 |
| SA [114] | 20.4068 | MFA | 4.3374 | 21.255 |
| | | GA | 3.1411 | 15.392 |
| | | FAGA | 4.649 | 22.782 |
| CSA [116] | 19.5521 | MFA | 3.4827 | 17.812 |
| | | GA | 2.2864 | 11.694 |
| | | FAGA | 3.7943 | 19.406 |
| DJaya [4] | 18.8404 | MFA | 2.7710 | 14.708 |
| | | GA | 1.5747 | 8.3581 |
| | | FAGA | 3.0826 | 16.362 |

**Table F.12**

*CTI using the NLP formulation for the IEEE 15-bus network*

| P/R | MFA | GA | FAGA | P/R | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|
| | CTI | CTI | CTI | | CTI | CTI | CTI |
| 1 | 0.27192 | 0.20250 | 0.27283 | 42 | 0.20000 | 0.20248 | 0.20000 |
| 2 | 0.20021 | 0.20691 | 0.26908 | 43 | 0.41564 | 0.24179 | 0.38690 |
| 3 | 0.20684 | 0.20169 | 0.27565 | 44 | 0.29074 | 0.24035 | 0.28809 |
| 4 | 0.38088 | 0.23080 | 0.37773 | 45 | 0.24635 | 0.24007 | 0.27433 |
| 5 | 0.26344 | 0.22217 | 0.26634 | 46 | 0.74960 | 0.32804 | 0.36524 |
| 6 | 0.32155 | 0.21447 | 0.30853 | 47 | 0.20017 | 0.27387 | 0.20000 |
| 7 | 0.27452 | 0.21430 | 0.27376 | 48 | 0.25592 | 0.20036 | 0.32076 |
| 8 | 0.27888 | 0.21752 | 0.27701 | 49 | 0.24526 | 0.25135 | 0.24884 |
| 9 | 0.49556 | 0.20007 | 0.36414 | 50 | 0.71526 | 0.25415 | 0.41813 |
| 10 | 0.26661 | 0.30249 | 0.22716 | 51 | 0.22361 | 0.20014 | 0.23031 |
| 11 | 0.29066 | 0.24161 | 0.29234 | 52 | 0.36697 | 0.20016 | 0.30300 |
| 12 | 0.23533 | 0.27319 | 0.22315 | 53 | 0.20098 | 0.20016 | 0.20000 |
| 13 | 0.28149 | 0.21233 | 0.28906 | 54 | 0.28378 | 0.29056 | 0.28606 |
| 14 | 0.22659 | 0.24462 | 0.24636 | 55 | 0.21609 | 0.30199 | 0.22190 |
| 15 | 0.21415 | 0.24106 | 0.23697 | 56 | 0.26451 | 0.20003 | 0.26351 |
| 16 | 0.21851 | 0.24428 | 0.24022 | 57 | 0.20000 | 0.20009 | 0.20000 |
| 17 | 0.24207 | 0.20005 | 0.22522 | 58 | 0.33770 | 0.20008 | 0.33260 |
| 18 | 0.26418 | 0.20007 | 0.22594 | 59 | 0.28796 | 0.20135 | 0.26646 |
| 19 | 0.20402 | 0.20727 | 0.20351 | 60 | 0.36205 | 0.20169 | 0.30750 |
| 20 | 0.21032 | 0.26991 | 0.20686 | 61 | 0.23714 | 0.20025 | 0.20869 |
| 21 | 0.2449 | 0.26651 | 0.23224 | 62 | 0.20000 | 0.20628 | 0.20243 |
| 22 | 0.20223 | 0.26957 | 0.20073 | 63 | 0.20000 | 0.29184 | 0.20053 |
| 23 | 0.33315 | 0.20015 | 0.27222 | 64 | 0.39788 | 0.29994 | 0.37551 |
| 24 | 0.39635 | 0.20001 | 0.38326 | 65 | 0.23487 | 0.20007 | 0.23525 |
| 25 | 0.20921 | 0.20000 | 0.23524 | 66 | 0.48308 | 0.20691 | 0.47639 |
| 26 | 0.31469 | 0.27174 | 0.31481 | 67 | 0.30347 | 0.35741 | 0.30810 |
| 27 | 0.36723 | 0.32258 | 0.35392 | 68 | 0.32832 | 0.38202 | 0.33295 |
| 28 | 0.44449 | 0.20353 | 0.44979 | 69 | 0.58471 | 0.20013 | 0.28149 |
| 29 | 0.32041 | 0.20012 | 0.33182 | 70 | 0.64250 | 0.20030 | 0.25892 |
| 30 | 0.26942 | 0.36868 | 0.26771 | 71 | 0.21768 | 0.20016 | 0.21860 |
| 31 | 0.30942 | 0.20487 | 0.30188 | 72 | 0.20075 | 0.20005 | 0.20000 |
| 32 | 0.36309 | 0.40260 | 0.33389 | 73 | 0.20056 | 0.21167 | 0.20000 |
| 33 | 0.23709 | 0.23879 | 0.26506 | 74 | 0.20215 | 0.20030 | 0.20026 |
| 34 | 0.26106 | 0.22444 | 0.23028 | 75 | 0.20123 | 0.20069 | 0.20000 |
| 35 | 0.22315 | 0.23047 | 0.22402 | 76 | 0.20053 | 0.20000 | 0.20000 |
| 36 | 0.21667 | 0.22416 | 0.21651 | 77 | 0.20096 | 0.20000 | 0.20060 |

| P/R | MFA | GA | FAGA | P/R | MFA | GA | FAGA |
|---|---|---|---|---|---|---|---|
| | CTI | CTI | CTI | | CTI | CTI | CTI |
| 37 | 0.24265 | 0.20376 | 0.25201 | 78 | 0.20000 | 0.20053 | 0.20000 |
| 38 | 0.27723 | 0.20036 | 0.27739 | 79 | 0.20001 | 0.20014 | 0.20000 |
| 39 | 0.23020 | 0.20020 | 0.24263 | 80 | 0.24223 | 0.22486 | 0.24347 |
| 40 | 0.36906 | 0.20420 | 0.31257 | 81 | 0.20045 | 0.20014 | 0.20000 |
| 41 | 0.20624 | 0.20879 | 0.20751 | 82 | 0.20000 | 0.20014 | 0.20000 |

**Figure F.6**

*Total operational time compared to the literature for the proposed algorithms.*

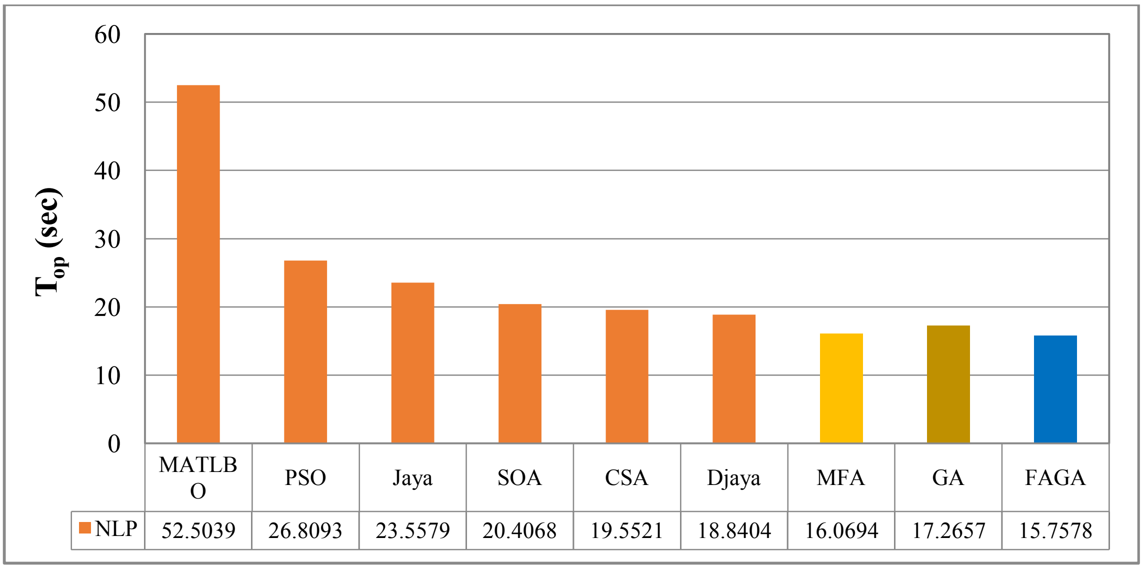
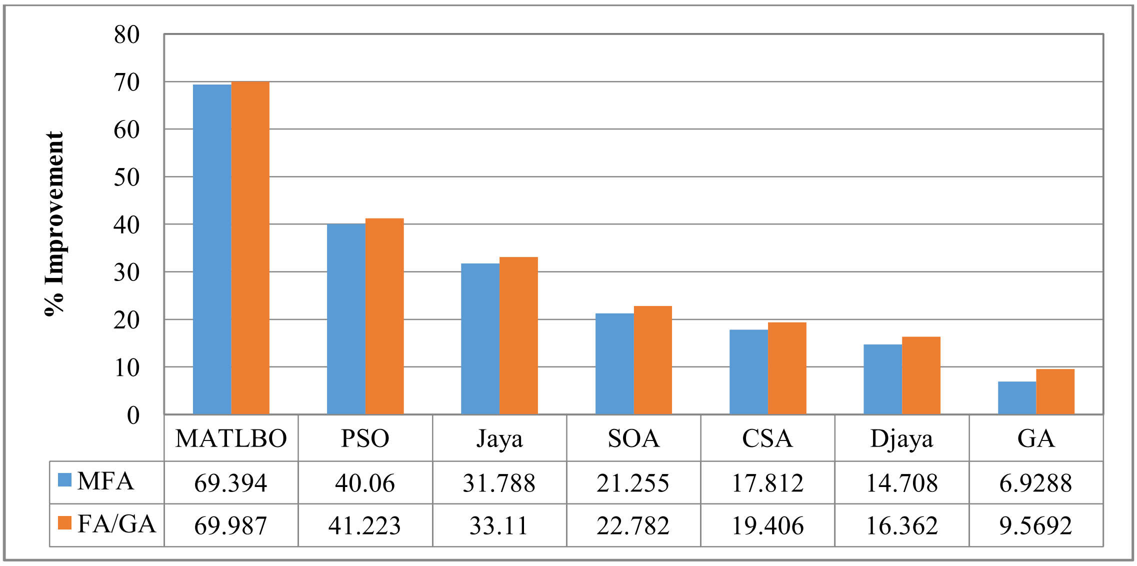



**Figure F.7**

*Percentage improvement of the proposed methods compared to other algorithms in the literature for IEEE 15-bus network in terms of the net relay operational time*



# Appendix G

## Matlab Codes: Test System I

### Modified FA with LP formulation

```
function Tpr=cost(x)
CTR=[300/5, 200/5, 200/5, 300/5, 200/5, 400/5];
PS=[5 1.5 5 4 2 2.5];
FCpr=[1978.9, 1525.7, 1683.9, 1815.4, 1499.66, 1766.3];
FCbc=[175, 545, 617.22, 466.17, 384, 145.34];



Tpr=x(1)*0.14/(((FCpr(1)/(PS(1)*CTR(1)))^0.02)-1)+
x(2)*0.14/(((FCpr(2)/(PS(2)*CTR(2)))^0.02)-1)+ ...
    x(3)*0.14/(((FCpr(3)/(PS(3)*CTR(3)))^0.02)-1)+
x(4)*0.14/(((FCpr(4)/(PS(4)*CTR(4)))^0.02)-1)+ ...
    x(5)*0.14/(((FCpr(5)/(PS(5)*CTR(5)))^0.02)-1)+
x(6)*0.14/(((FCpr(6)/(PS(6)*CTR(6)))^0.02)-1);

    T1pr=x(1)*0.14/(((FCpr(1)/(PS(1)*CTR(1)))^0.02)-1);
    T2pr=x(2)*0.14/(((FCpr(2)/(PS(2)*CTR(2)))^0.02)-1);
    T3pr=x(3)*0.14/(((FCpr(3)/(PS(3)*CTR(3)))^0.02)-1);
    T4pr=x(4)*0.14/(((FCpr(4)/(PS(4)*CTR(4)))^0.02)-1);
    T5pr=x(5)*0.14/(((FCpr(5)/(PS(5)*CTR(5)))^0.02)-1);
    T6pr=x(6)*0.14/(((FCpr(6)/(PS(6)*CTR(6)))^0.02)-1);
    TPR=[T1pr T2pr T3pr T4pr T5pr T6pr];

    T5bc=x(5)*0.14/(((FCbc(1)/(PS(5)*CTR(5)))^0.02)-1);
    T4bc=x(4)*0.14/(((FCbc(2)/(PS(4)*CTR(4)))^0.02)-1);
    T1bc=x(1)*0.14/(((FCbc(3)/(PS(1)*CTR(1)))^0.02)-1);
    T6bc=x(6)*0.14/(((FCbc(4)/(PS(6)*CTR(6)))^0.02)-1);
    T3bc=x(3)*0.14/(((FCbc(5)/(PS(3)*CTR(3)))^0.02)-1);
    T2bc=x(2)*0.14/(((FCbc(6)/(PS(2)*CTR(2)))^0.02)-1);
    TBC= [T5bc T4bc T1bc T6bc T3bc T2bc];

for j=1:length(TBC)
    Violation(j)=TBC(j)-TPR(j);
end

disp(['T1(pr) = ', num2str(TPR(1))])
disp(['T2(pr) = ', num2str(TPR(2))])
disp(['T3(pr) = ', num2str(TPR(3))])
disp(['T4(pr) = ', num2str(TPR(4))])
disp(['T5(pr) = ', num2str(TPR(5))])
disp(['T6(pr) = ', num2str(TPR(6))])

disp(['T1(BC) = ', num2str(TBC(1))])
disp(['T2(BC) = ', num2str(TBC(2))])
disp(['T3(BC) = ', num2str(TBC(3))])
disp(['T4(BC) = ', num2str(TBC(4))])
disp(['T5(BC) = ', num2str(TBC(5))])
disp(['T6(BC) = ', num2str(TBC(6))])
```

```
disp(['T5(bc) - T1(pr) = ', num2str(Violation(1))])
disp(['T4(bc) - T2(pr) = ', num2str(Violation(2))])
disp(['T1(bc) - T3(pr) = ', num2str(Violation(3))])
disp(['T6(bc) - T4(pr) = ', num2str(Violation(4))])
disp(['T3(bc) - T5(pr) = ', num2str(Violation(5))])
disp(['T2(bc) - T6(pr) = ', num2str(Violation(6))])
end

function [g,geq]=constraint(x)
CTR=[300/5, 200/5, 200/5, 300/5, 200/5, 400/5];
FCpr=[1978.9, 1525.7, 1683.9, 1815.4, 1499.66, 1766.3];
PS=[5 1.5 5 4 2 2.5];
FCbc=[175, 545, 617.22, 466.17, 384, 145.34];
CTI=0.2;
g=[
  x(1)*0.14/(((FCpr(1)/(PS(1)*CTR(1)))^0.02)-1)+CTI-
x(5)*0.14/(((FCbc(1)/(PS(5)*CTR(5)))^0.02)-1);
  x(2)*0.14/(((FCpr(2)/(PS(2)*CTR(2)))^0.02)-1)+CTI-
x(4)*0.14/(((FCbc(2)/(PS(4)*CTR(4)))^0.02)-1);
  x(3)*0.14/(((FCpr(3)/(PS(3)*CTR(3)))^0.02)-1)+CTI-
x(1)*0.14/(((FCbc(3)/(PS(1)*CTR(1)))^0.02)-1);
  x(4)*0.14/(((FCpr(4)/(PS(4)*CTR(4)))^0.02)-1)+CTI-
x(6)*0.14/(((FCbc(4)/(PS(6)*CTR(6)))^0.02)-1);
  x(5)*0.14/(((FCpr(5)/(PS(5)*CTR(5)))^0.02)-1)+CTI-
x(3)*0.14/(((FCbc(5)/(PS(3)*CTR(3)))^0.02)-1);
  x(6)*0.14/(((FCpr(6)/(PS(6)*CTR(6)))^0.02)-1)+CTI-
x(2)*0.14/(((FCbc(6)/(PS(2)*CTR(2)))^0.02)-1);

  0.1-x(1)*0.14/(((FCpr(1)/(PS(1)*CTR(1)))^0.02)-1);
  0.1-x(2)*0.14/(((FCpr(2)/(PS(2)*CTR(2)))^0.02)-1);
  0.1-x(3)*0.14/(((FCpr(3)/(PS(3)*CTR(3)))^0.02)-1);
  0.1-x(4)*0.14/(((FCpr(4)/(PS(4)*CTR(4)))^0.02)-1);
  0.1-x(5)*0.14/(((FCpr(5)/(PS(5)*CTR(5)))^0.02)-1);
  0.1-x(6)*0.14/(((FCpr(6)/(PS(6)*CTR(6)))^0.02)-1);

  x(1)*0.14/(((FCpr(1)/(PS(1)*CTR(1)))^0.02)-1)-0.5;
  x(2)*0.14/(((FCpr(2)/(PS(2)*CTR(2)))^0.02)-1)-0.5;
  x(3)*0.14/(((FCpr(3)/(PS(3)*CTR(3)))^0.02)-1)-0.5;
  x(4)*0.14/(((FCpr(4)/(PS(4)*CTR(4)))^0.02)-1)-0.5;
  x(5)*0.14/(((FCpr(5)/(PS(5)*CTR(5)))^0.02)-1)-0.5;
  x(6)*0.14/(((FCpr(6)/(PS(6)*CTR(6)))^0.02)-1)-0.5;
   ];
geq=[];


function Fireflyx
clc;
clear;
format long;
rng('default')
Lb=[0.1 0.1 0.1 0.1 0.1 0.1];
Ub=[1.1 1.1 1.1 1.1 1.1 1.1];
u0=(Lb+Ub)/2;
```

```
para=[25 2000 0.8 0.2 1];
[u,fval,NumEval]=ffa_mincon(@cost,@constraint,u0,Lb,Ub,para);
disp('Directional overcurrent relay coordination problem for six relay
system...');
fprintf('\n\nTMS 1 = %g\nTMS 2 = %g\nTMS 3 = %g\nTMS 4 = %g\nTMS 5 =
%g\nTMS 6 = %g\n'...
    ,u(1),u(2),u(3),u(4),u(5),u(6))
fprintf('\nBest overall min. operating time :%g\n\n',fval)
total_number_of_function_evaluations=NumEval


function [nbest,fbest,NumEval]...
           =ffa_mincon(fhandle,nonhandle,u0, Lb, Ub, para)
if nargin<6,
    para=[25 2000 0.8 0.2 1];
end

if nargin<5,
    Ub=[];
end

if nargin<4,
    Lb=[];
end

if nargin<3,
disp('Usuage: FA_mincon(@cost, @constraint,u0,Lb,Ub,para)');
end

n=para(1);
MaxGeneration=para(2);
alpha=para(3);
betamin=para(4);
gamma=para(5);

NumEval=n*MaxGeneration;

if length(Lb) ~=length(Ub),
    disp('Simple bounds/limits are improper!');
    return
end

d=length(u0);
zn=ones(n,1)*10^100;
[ns,Lightn]=init_ffa(n,d,Lb,Ub,u0);
for k=1:MaxGeneration,
alpha=alpha_new(alpha,MaxGeneration);

for i=1:n,
   zn(i)=Fun(fhandle,nonhandle,ns(i,:));
   Lightn(i)=zn(i);
end

[Lightn,Index]=sort(zn);
ns_tmp=ns;
for i=1:n,
 ns(i,:)=ns_tmp(Index(i),:);
end

nso=ns;
 Lighto=Lightn;
```

```
 nbest=ns(1,:);
 Lightbest=Lightn(1);
 fbest=Lightbest;
 % Move all fireflies to the better locations
 [ns]=ffa_move(n,d,ns,Lightn,nso,Lighto,nbest,...
     Lightbest,alpha,betamin,gamma,Lb,Ub);
     plot(k,fbest,'b-x')% this plots the graph
                    xlabel('Iteration number');
                 ylabel('fitness value');
                  hold on
            grid on
end

      plot(k,fbest,'b-x')% this plots the graph
                    xlabel('Iteration number');
                 ylabel('fitness value');
                  hold on
            grid on
function alpha=alpha_new(alpha,NGen)
delta=1-(10^(-4)/0.9)^(1/NGen);
alpha=(1-delta)*alpha;
end
function [ns]=ffa_move(n,d,ns,Lightn,nso,Lighto,...
             nbest,Lightbest,alpha,betamin,gamma,Lb,Ub)
scale=abs(Ub-Lb);

for i=1:n,
   for j=1:n,
      r=sqrt(sum((ns(i,:)-ns(j,:)).^2));
      % Update moves
if Lightn(i)>Lighto(j),
   beta0=1;
   beta=(beta0-betamin)*exp(-gamma*r.^2)+betamin;
   tmpf=alpha.*(rand(1,d)-0.5).*scale;
   ns(i,:)=ns(i,:).*(1-beta)+nso(j,:).*beta+tmpf;
      end
   end
end
 [ns]=findlimits(n,ns,Lb,Ub);
function [ns]=findlimits(n,ns,Lb,Ub)
for i=1:n,
  ns_tmp=ns(i,:);
  I=ns_tmp<Lb;
  ns_tmp(I)=Lb(I);
  J=ns_tmp>Ub;
  ns_tmp(J)=Ub(J);
  ns(i,:)=ns_tmp;
end
function z=Fun(fhandle,nonhandle,u)
z=fhandle(u);
z=z+getnonlinear(nonhandle,u);
end
function H=getH(g)
if g<=0,
    H=0;
else
    H=1;
end
function H=geteqH(g)
if g==0,
    H=0;
```

```
else
    H=1;
end
function Z=getnonlinear(nonhandle,u)
Z=0;
lam=40; lameq=40;
 [g,geq]=nonhandle(u);
for k=1:length(g),
    Z=Z+ lam*g(k)^2*getH(g(k));
end
for k=1:length(geq),
   Z=Z+lameq*geq(k)^2*geteqH(geq(k));
end
function [ns,Lightn]=init_ffa(n,d,Lb,Ub,u0)
if length(Lb)>0,
   for i=1:n,
   ns(i,:)=Lb+(Ub-Lb).*rand(1,d);
   end
else
   for i=1:n,
   ns(i,:)=u0+randn(1,d);
   end
end
Lightn=ones(n,1)*10^100;
```

## GA with LP formulation

```
rng default % For reproducibility

ObjFcn= @cost;
nvars=6;
lb=[0.1 0.1 0.1 0.1 0.1 0.1];          %Lower bound of the decision
variables
ub=[1.1 1.1 1.1 1.1 1.1 1.1];                      %Upper bound of the
decision variables
ConsFcn= @constraint;
options =
optimoptions('ga','PlotFcn',{@gaplotbestf,@gaplotchange},'PopulationSi
ze',200,...
'Display','iter','PenaltyFactor',10000,'MaxStallGenerations',200,'MaxG
enerations',400,'ConstraintTolerance',1.0000e-06);
[x,fval,exitFlag,output,population,scores] =
ga(ObjFcn,nvars,[],[],[],[],lb,ub,ConsFcn,options);
fprintf('The number of generations is: %d\n', output.generations);
fprintf('The number of function evaluations is: %d\n',
output.funccount);
fprintf('The best function value found is: %g\n', fval);
fprintf('\n\nTMS 1 = %g\nTMS 2 = %g\nTMS 3 = %g\nTMS 4 = %g\nTMS 5 =
%g\nTMS 6 = %g\nPS 1 = %g\nPS 2 = %g\nPS 3 = %g\nPS 4 = %g\nPS 5 =
%g\nPS 6 = %g\n'...
    ,x(1),x(2),x(3),x(4),x(5),x(6))
function state = gaplotchange(options, state, flag)

if(strcmp(flag,'init')) % Set up the plot
    xlim([1,options.MaxGenerations]);
    axx = gca;
    axx.YScale = 'log';
    hold on;
```

```
    xlabel Generation
    title('Log Absolute Change in Best Fitness Value')
end

best = min(state.Score);
if state.Generation == 0
    last_best = best;
else
      change = last_best - best;
      last_best = best;
    if change > 0
      plot(state.Generation,change,'xr');
    end
end
```

**FAGA with LP formulation**

Only tha main m.file is modified

```
rng default % For reproducibility

ObjFcn= @cost;
nvars=6;
lb=[0.1 0.1 0.1 0.1 0.1 0.1];
ub=[1.1 1.1 1.1 1.1 1.1 1.1];
ConsFcn= @constraint;

options =
optimoptions('ga','PlotFcn',{@gaplotbestf,@gaplotchange},'PopulationSi
ze',200,...
'Display',
'iter','PenaltyFactor',100,'MaxStallGenerations',200,'MaxGenerations',
400,...
'InitialPopulation',[0.1 0.1 0.1 0.1 0.1
0.1],'ConstraintTolerance',1.0000e-06);
[x,fval,exitFlag,output,population,scores] =
ga(ObjFcn,nvars,[],[],[],[],lb,ub,ConsFcn,options);
fprintf('The number of generations is: %d\n', output.generations);
fprintf('The number of function evaluations is: %d\n',
output.funccount);
fprintf('The best function value found is: %g\n', fval);
fprintf('\n\nTMS 1 = %g\nTMS 2 = %g\nTMS 3 = %g\nTMS 4 = %g\nTMS 5 =
%g\nTMS 6 = %g\nPS 1 = %g\nPS 2 = %g\nPS 3 = %g\nPS 4 = %g\nPS 5 =
%g\nPS 6 = %g\n'...
    ,x(1),x(2),x(3),x(4),x(5),x(6))
```

جامعة النجاح الوطنية

كليَّة الدراسات العليا

# خوارزمية اليراع–الجينية المهجنة من أجل التنسيق الأمثل لمرحلات زيادة التيار

إعداد

طارق حسام فقها

إشراف

د. ماهر خماش

قدمت هذه الرسالة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة القوى الكهربائية، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس–فلسطين.

2023

# خوارزمية اليراع-الجينية المهجنة من أجل التنسيق الأمثل لمرحلات زيادة التيار

**إعداد**
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**د. ماهر خماش**

## الملخص

**الخلفية النظرية:** تُستخدم مرحلات زيادة التيار الزائدة الاتجاهية لحماية نظام الطاقة لضمان التشغيل الآمن والموثوق والفعال. إن تنسيق المرحلات الزائدة التيار الاتجاهية هو مشكلة أمثل غير خطية ومقيدة للغاية. الهدف الأساسي من التحسين هو تقليل تجميع أوقات التشغيل للمرحلات الأولية، من خلال تحديد القيم المثلى لمتغيرات القرار كإعداد Time multiplier setting (TMS) وإعداد plug setting (PS).

**هدف البحث:** الهدف الرئيسي لهذه الدراسة هو تطوير خوارزمية تحسين هجينة تتكون من خوارزمية اليراع المعدلة والخوارزمية الجينية لإيجاد حلول أفضل.

**منهجية البحث:** أولاً، عدلت هذه الدراسة خوارزمية اليراع الأصلي للحصول على حل أمثل من خلال تحديث سطوع اليراع وتجنب المسافة بين اليراعات الفردية من أن تكون بعيدة جدًا. بالإضافة إلى ذلك، تم التحكم في الحركات العشوائية لإنتاج معدل تقارب مرتفع. ثانيًا، تم حل مشكلة التحسين باستخدام الخوارزمية الجينية القياسية. أخيرًا، تم استخدام الحل الذي تم الحصول عليه من خوارزمية اليراع المعدلة كحلول أولية للخوارزمية الجينية القياسية. تم اختبار خوارزمية اليراع المعدلة والخوارزمية الجينية والخوارزمية المهجنة المقترحة على أنظمة IEEE 3-bus و 8-bus و 9-bus و 15-bus.

**نتائج البحث:** تشير النتائج إلى فعالية وتفوق الخوارزميات المقترحة في تقليل وقت التشغيل الإجمالي للمرحلات الأولية مقارنة بالطرق الأخرى المذكورة في الأدبيات لتنسيق مرحلات زيادة التيار.

**استنتاجات البحث:** بالمقارنة مع خوارزمية اليراع المعدلـــة والخوارزميـــة الجينيـــة القياســـية، قللـــت الخوارزمية الهجينة المقترحة من وقت فاصل التنسيق بين أزواج التتابع الأولية والنسخ الاحتياطي.

**الكلمات المفتاحية:** الخوارزميات الهجينة ، خوارزمية اليراع ، الخوارزمية الجينية.