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Optimal Overcurrent Relay Solutions for Protection Coordination using Metaheuristics Approaches with Penalty Function Method

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ABSTRACT

This paper presents the development of overcurrent relay coordination (OCRC) problem formulation by implementing five well known metaheuristic algorithms that are Ant Lion Optimizer (ALO), Moth Flame Optimizer (MFO), Grey Wolf Optimizer (GWO), Particles Swarm Optimizer (PSO) and Barnacles Matting Optimizer (BMO). The algorithms are assisted with penalty function method during the selection of new agents/ offsprings to confirm the generations that violated the constraints are superseded during the next generation selection. The OCRC is established by manipulating the current known as plus setting (PS) and time delay known as time multiplier setting (TMS) parameters. The optimized value of the TMS and PS will be selected using the algorithms to ensure the minimize result of the objective function. The algorithms are tested to three test systems which are IEEE 3 bus, 8 bus and 15 bus system to validate the efficiency and superiority of the proposed algorithms. The obtained results from those five algorithms are then compared. The simulation results show that MFO, BMO and GWO perform better objective function result and efficiently optimize the TMS and PS value of the OCRC problem without neglecting the inequality constraints.

1. Introduction

The role of the protection devices has facing enormous challenges due to the evolution of the commercial power supply. The increasing load due to the grown of human population around the world has leading to the interest towards distributed generation (DG) application. The clearest consequence of the DG is the sympathetic overcurrent relay tripping activities. This activity could have disturbed the operational of the electrical supply and concurrently affected the domestic and commercial services in direct [1]. The tripping event will be resulted to the emotional and financial losses. Numerous efforts have been made to analyze the various causes of the sympathetic trip phenomenon and to prevent false sympathetic trips. One of the solutions is to ensure that the overcurrent relay parameters are correctly arranged and coordinated to withstand the abnormal

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condition due to faults and short circuit [2]. According to statistical research evidence, instead of the genuine fault, the occurrence of tripping activities can be attributed to inadequate or improper coordination settings of the relays [3]. Related to this, protection engineer should be acquainted about tripping characteristics of various protective relays. The optimize tripping sequence shall be fulfilled by two parameters which are Time Multiplier Setting (TMS) and Plug Setting (PS) without eliminating the coordination time interval (CTI) constraint.

This article intends to recognize the concerns and challenges faced during the preparation of the novel OCRC setting. In addition, focused on the selectivity of the optimize value of TMS and PS while considering the CTI in between primary and secondary relays using the metaheuristics algorithm. This research is implemented the standard inverse (SI)/ normal inverse (NI) characteristic curve of the inverse definite minimum time (IDMT) relay which comply to the IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems [4]. Thus, this article recommends five well known metaheuristic algorithms: Ant Lion Optimizer (ALO), Moth Flame Optimizer (MFO), Grey Wolf Optimizer (GWO), Particles Swarm Optimizer (PSO) and Barnacles Matting Optimizer (BMO) to be implemented in simulation studies.

1.1 Literature Survey and Motivation

The philosophy of protection devices is to divide the system into distinct zones which are having an ability to protect individually and cut off during fault occurrence. In general, power system can be classified into zones of protection which are generators, transformers, motors, busbars and lines. The protection zones are overlapping on each other at some positions to indicate that more than a single set of protection devices should operate if any fault occurs in the areas. Every zone of protection is facilitating with relays and represented as secondary zone for the nearby zones. All the equipment in the system should be protected by primary and back-up relays. The primary relay is known as the first shield for the element involved during the fault occurrence. It should operate immediately when there is fault detected. There are various primary protection devices are installed to protect the component inside the system. Nevertheless, they are not sensing the same fault and might not compulsory to be located at the same equipment. The back-up relay also known as the secondary protection devices. This secondary relay will operate when the primary relay does not work appropriately. The **Error! Reference source not found.** shows, four relays could be sensing the fault current at X location, however only the immediate nearby relay (yellow colored) which acted as primary will react and operate the circuit breaker to quickly isolate the fault. The next relay (orange colored) will be represented as a back-up relay. Primary and back-up relays could be selective when the back-up relay's TMS and PS value is set more than TMS and PS value of the primary relay. The value of TMS and PS will affect the relay operating time proportionally. The TMS is a delaying in trip operation after the device has sensed and measured the overcurrent occurrence in the system. The tripping time of an overcurrent relay can be moved up or made slower by adjusting the TMS value. Increasing the TMS value will shifts the curve upwards the graph and relay will operate in a longer-time delay. The PS will determine at which current point the relay will start to response to the overcurrent, adjusting the PS value will move curve left and right.

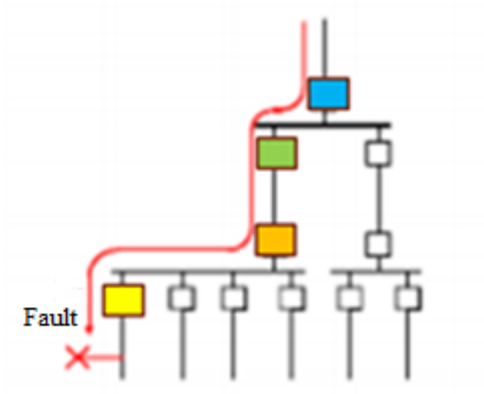

Fig. 1. Example of short circuit flow in radial system

Traditionally, the trial-and-error approach were used to set the relays curve from top one to the next with selected characteristic curve type as in Table 1, PS and TMS value by the qualified and experience engineer. However, this method requires large number of iterations in order to achieve the optimal relay setting and suffered a slow rate of convergence [1]. Due to the complexity of the modern interconnected power system, trial and error approach is no more compatible to be used which involved time consuming and not optimal. In order to overcome this complexity of the approaches system besides to search for the optimal overcurrent relays coordination setting at the same time, a new efficient solution should be developed. In 1960s, the power distribution networks are used to support the local neighborhood activities and transmitted through radial small-scale system. This situation has acknowledged the implementation of Trial and Error approach [2] to perform the overcurrent relays coordination setting. In this technique, fault analysis is conducted at the first place to configure the maximum fault value at the designated lines or busbars. Relay at the farthest are set first followed by the next level and so forth. The process is repeated until all relays inside the system is taken into account. The repetitive process of this technique has lengthier convergence time as its highlighted as the drawbacks of this approach [3]. In addition, the generated results are not optimal due to the factors of defective decision and only discrete variables are considered. In late 1960s, topological analysis method has gained good recognition which uses the graph theory approach to determine break points [4]. The final TMS and PS is then obtained by selecting the point that touch the maximum fault value. This step is repeated for the upper level of overcurrent relay. However, if the operating time for the relay that is nearest to the source is exceeding the permitted time, the process of TMS and PS selection will be reiterated until it reaches permitted time. The solution found using this method is better as compared to trial and error approach but still not optimal [5] and lengthy process. In 1988, Linear Programming (LP) approach was presented in the frame of optimization method [6, 7]. This technique has gained interest from the researchers due to its simplicity which involved fixed value of PS variables and only TMS is determined. However, due to the assumption of the PS value, the obtained results is not optimal [8]. The reiterating process is possible to be performed if applied for the radial small-scale distribution system. Nevertheless, it is impractical for meshed distribution network since an economic and effective overcurrent relays coordination setting for meshed or multi-sources power distribution network requires tedious and time-consuming affair. The slow convergence rate with large number of iterations to reach a suitable relay setting is the main drawback for the conventional methods.

The increasing complexity of large-scale computing issues over the last four decades has necessitated the development of more effective meta-heuristic methodologies. Meta-heuristic algorithms, in general, have been used to identify optimum solutions to large-scale computing issues and have grown in popularity due to their decreased complexity and enhanced efficiency when compared to other conventional methods [9]. In 1986, Fred Glover created the term "metaheuristic" to describe a heuristic procedure having non-problem-specific characteristics [10]. Meta-heuristic methods have been implemented to various engineering field [11-16] which has proven being able to produce an optimized solution. Meta-heuristic algorithms are typically motivated by animal/insect behavior, nature, evolutionary notions, and sorts of natural events. The bulk of meta-heuristics is inspired by nature, including Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA). Also, some of them are not influenced by nature, such as Iterated Local Search (ILS) and Tabu Search (TS) [17]. Metaheuristics approaches in solving OCRC problem have been began with Genetic Algorithm (GA) [18]. GA has befitting as the most popular method in this area in early 1990s. Improvement to GA called Continuous Genetic Algorithm (CGA) has been made in [19] where chromosome in CGA is not need to be decoded and able to produce faster results compared to binary GA. An improvement method called as fuzzy based Genetic Algorithm [20] developed to solve the mis-coordination problem which updated the weighting factors during simulation. In [21] called as Particle Swarm Optimization (PSO) method has proven to give out better result compared to conventional GA and modern GA. The revolution of the algorithm is continued by Differential Evolution (DE) and Modified Differential Evolution (MDE) method as in [22] , Invasive weed optimization[23]. In order to generate better performance of MDE, hybrid method has been developed in [24], Rooted Tree Optimizations (RTO) [25], Markov decision processes (MDPs) [26], Cuckoo Search Algorithm is developed in [27] and Electromagnetic Field Optimization (EFO) method in [28]. The No Free Lunch (NFL) theorem [29] has mentioned that there is no meta-heuristic algorithm that could afford a superior performance than others in solving all optimization problems. In other words, a particular algorithm may present promising results for a certain problem but may not for the other type of problems. The NFL theorem has clearly stated, researchers are authorized to enhance or modify the recent algorithms for solving different problems or recommend new algorithms to deliver competitive results compared to the current algorithms [30]. Applying this modern nature inspired based algorithms to solve the OCRC problem has allowed continuous TMS and PS values to be used and be able to optimize the relay operating time.

Table 1
Types of time-current characteristic curve [31]

Curve type	k	α
Standard inverse (SI)	0.14	0.02
Very inverse (VI)	13.5	1.0
Extremely inverse (EI)	80.0	2.0

1.2 Contribution and Paper Organization

The literature nurtured several concerns while describing challenges in terms of using traditional OCRC method especially for large scale system. These challenges and concerns are in terms of protection sensitivity, security and stability to accommodate steady power sources to the load. This showed the need to develop flexible and optimal OCRC schemes to securely protect the modern distribution mesh networks. In this work, an optimal OCRC scheme based on using five modern metaheuristic optimization algorithms: Ant Lion Optimizer (ALO), Moth Flame Optimizer (MFO), Grey Wolf Optimizer (GWO), Particles Swarm Optimizer (PSO) and Barnacles Matting Optimizer (BMO) to provide a fast response overcurrent relay and improve the OCRC performance for a power network. The contributions and novelty of this simulation-based research are as follows:

- Developed OCRC problem formulation with the assistance of five new methaheuristic algorithms (ALO, MFO, GWO, PSO and BMO) in order to choose the optimize TMS and PS value based on coordination time interval (CTI) factor. The recommended schemes goal is to minimize the total tripping time for overcurrent relays inside the system. In advanced, the schemes are able to avoid any sympathy trips or miscoordination in between primary and secondary relays. This sympathy trips might happened if the coordination time interval constraint is violated/ ignored by the proposed schemes. In order to avoid distruption to the power supply system, this CTI factor is the most important to be taken care while proposing/ developing the problem formulation.
- Modern metaheuristic optimization algorithms (ALO, MFO, GWO, PSO and BMO) are established and utilized in this research to solve the OCRC problem and enhance the performance of coordination scheme. The algorithms showed an effective competency to accomplish a global solution for different engineering problems and outperformed common algorithms such as DE and GA. Therefore, this work introduces and employs these modern algorithms in solving complex OCRC problems for a power distribution network. To the authors knowledge, there are no studies on using and comparing these modern algorithms in solving modern OCRC problems in a modern mesh system. In addition, a comparison analysis is perform using the modern metaheuristic optimization algorithms in OCRC scheme on three different IEEE test cases (IEEE 3 bus, 8 bus and 15 bus) to demonstrate the effectiveness of the proposed algorithm. In this work, the optimization algorithms (ALO, MFO, GWO, PSO and BMO) are integrated with the penalty function method to against the premature convergence and opposed the selection of any violated agents towards the coordination constraints in the next iteration process.
- Lastly, for fair comparison purposes, same parameter boundaries and constraints values were considered for each optimization algorithms employed in this work using normal inverse (NI) characteristic curve. Algorithms that outperformed (in terms of ability to reduce the total tripping time and without/ low constraints violations) compared to the other methods are then selected as the noble method for that particular test cases. Unlike the previous studies, the sensitivity of the proposed optimal OCRC scheme has been examined and significantly improved especially for the modern mesh power system.

In section 2, the formulation of the OCRC problem is described in detail complete with objective function, problem constraints and etc. This paper highlighted the advantages and drawbacks of the selected approaches in section 3. In section 4, formulation of the penalty function method to assist the algorithms is discussed. Then followed by discussion to the metaheuristic's simulation studies of the selected algorithms to solve the OCRC problem in section 5. Finally, this article is concluded in section 6.

2. Problem Formulation

The objective of the coordination problem is minimizing the total operating time of the primary relays while considering the primary and backup relays' time interval in between 0.2s – 0.5s. The minimization of the relay's operating time is associated to the optimize value of TMS and PS. To optimize the nonlinear objective function, various nonlinear inequality constraints shall be satisfied.

2.1 Objective Function

The objective function is possible to be achieved if relay parameters contraints and coordination constraints are fulfilled. The objective function is the total operating time of the primary relays as follows:

Minimize: $$OF = \sum_{i=1}^{n} \delta_i T_i \quad (1)$$

Where δ_i is the weight of relay *i* and *n* is the number of relays inside the system. While T_i is the operating time of primary relay. Generally the value of δ_i is set as one, hence Eq. (1) becomes:

$$OF = \sum_{i=1}^{n} T_i \quad (2)$$

Relay operating time is define by International Electrotechnical Commission (IEC) standard [31] as:

$$T_i = TMS_i \times \frac{k}{\left(\frac{I_{sc}}{PS_i}\right)^{\alpha} - 1} \quad (3)$$

where PS_i is plug setting for relay *i*, TMS_i is time multiplier setting for relay *i*, I_{sc} is short circuit current which seen by relay *i*

2.2 Selection of PS

The PS boundaries are in between maximum load demand and minimum fault current. The OCRC picks up on 125% of full load current, I_n as a lower bound and 67% of minimum fault current I_f is considered in this article. Taking into account that the selection of the PS has to consider the current transformer (CT) rating for each of the relays' installed inside the system.

The boundary of the PS can be calculated as:

$$PS_i^{\min} \le PS_i \le PS_i^{\max} \quad (4)$$

Where,

$$PS_{\min} = 1.25 \times I_n \quad (5)$$

$$PS_{\max} = \frac{2}{3} \times I_{f\min} \quad (6)$$

I_n is the maximum load demand which protected by the relay *i*. $I_{f\,min}$ is the minimum value of current which is detected as fault by relay *i*. The PS could be expressed in the form of array arrangement as:

$$PS\ array = [PSmin, PSmin + PS, PSmin + PS * 2, PSmin + PS * 3, \dots PSmax] \quad (7)$$

2.3 Selection the TMS

The selection of the TMS must be varies according to the characteristic curve type. The boundary of TMS is given as

$$TMS_i^{\min} \leq TMS_i \leq TMS_i^{\max} \tag{8}$$

The TMS value is the time delay that varies from 0.1 to 1.1 [32]. Where TMS_{min} is minimum limit and TMS_{max} is maximum limit value of TMS for relay *i.* The TMS could be expressed in the form of array arrangement as

$$TMSarray = [TMSmin, TMSmin + TMS, TMSmin + TMS * 2, TMSmin + TMS * 3, \ldots TMSmax] \tag{9}$$

This paper concentrated on time-current coordination so that relay operating time relates to the magnitude of the fault. In addition, the magnitude of the fault as follows

$$If = \begin{bmatrix} Ia, b & Ia+1, b & \cdots & Ia_{max}, b \\ Ia, b+1 & Ia+1, b+1 & \vdots & Ia_{max}, b+1 \\ \vdots & \vdots & & \vdots \\ Ia, b_{max} & Ia+1,\ b_{max} & \cdots & Ia_{max},\ b_{max} \end{bmatrix} \tag{10}$$

If contains the current magnitude of each relays that is range in columns and fault location range in rows. The TMS values varies with the different curve characteristics type as in Table 1. The fault occurances location and magnitude might be considered as another constraint in OCRC problem to identify the Overcurrent relay's task as a primary or secondary relays inside the system.

2.4 Target Coordination

The OCRC target is to confirm the primary relays to response/ trip in advanced instead of backup relays within the allowable time range. The range is considering the circuit breaker opening time 0.08s (50Hz, 5 cycles), over travel 0.1s and safety factor 0.12s to 0.22s. This range is called as coordination time interval (CTI) to ensure no cascading in between devices curve is happened and the relays inside the system shall be well arranged according to the predetermined setting values.

$$CTI = T_{bc} - T_{pr} \tag{11}$$

Where T_{pr} is primary relay time operating, T_{bc} is the back-up relay time operating to accomplish the coordination intention which to avoid the sympathy trips amongs the relays.

$$CTI_i^{\min} \leq CTI_i \leq CTI_i^{\max} \tag{11}$$

$$0.2\,\text{seconds} \leq CTI_i \leq 0.5\,\text{seconds} \tag{12}$$

3. Metaheuristics Approaches

This section summarizes the five recent nature inspired algorithms that are famously applied in various engineering field especially related to power system problem. These five algorithms being selected due to their simplicity of parameter adjustment and more importantly proven able to solve the power system problems. Over the last decades, meta-heuristic optimization algorithms have attracted interest among researchers from different fields of application such as engineering, computer science, bio-medical and etc [33-35]. These optimization methods are recommended to alleviate the aforementioned disadvantages of the conventional methods. The meta-heuristic method have becoming remarkable among researchers due to factors of simplicity, flexibility, derivation-free mechanism and local optimal avoidance [36]. Meta-heuristic is generally divided into classes of single-solution-based and population-based solutions. The single-based solution begins with single candidate solution which then enhanced over the iteration courses. On the other hand, for population-based, the methods are performed using a group of solutions. The process begins with random variety of solutions and improves over the iteration courses. Meta-heuristic is classified into three main clusters which are evolutionary algorithm (EA), physics-based (PB) and swarm intelligence (SI). Population based solution is having advantages compared to Single based solution [37] from the scope of sharing information in between particles or variables for wide search space, particles among population help each other to avoid local trap and having better search space exploration rate. The recent applied method to solve the overcurrent relays coordination problem is summarizing in Figure 2.

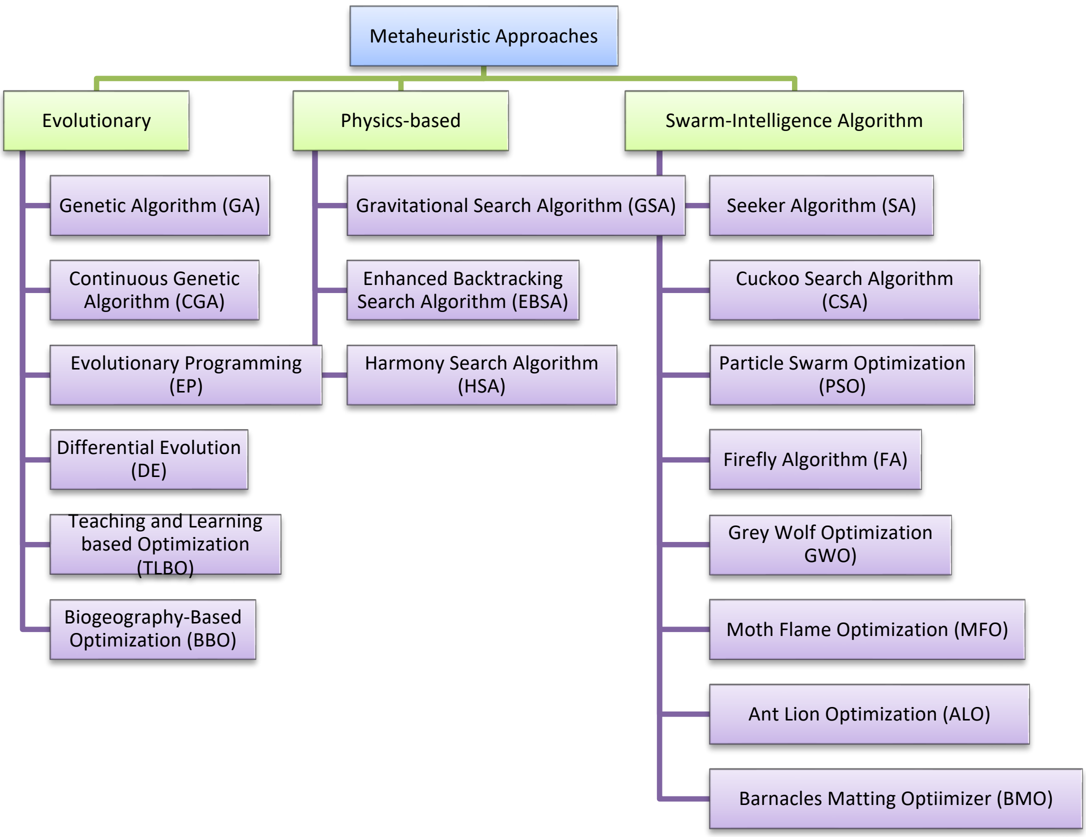

Fig. 2. Classification of metaheuristic approaches

3.1 Barnacles Matting Optiimizer (BMO)

Barnacles are classified and recognized as sessile organisms which living deep in the ocean (as shown in Figure 3). They are commonly found attached permanently to solid substance such as corals, rocks, ships and even to the sea turtle. They are also known as hermaphroditic organisms which have both male and female reproduction system and one of the unique features of barnacles is their penis size can stretch to multiple times compared to the length of their body (up to seven to eight times). The mating behavior of barnacles happened in two ways: by the normal copulation and sperm-cast. For normal copulation, the male barnacle will knock the female barnacle and the mating process is happened naturally. Meanwhile, sperm-cast will take place for mating of the isolated barnacles.

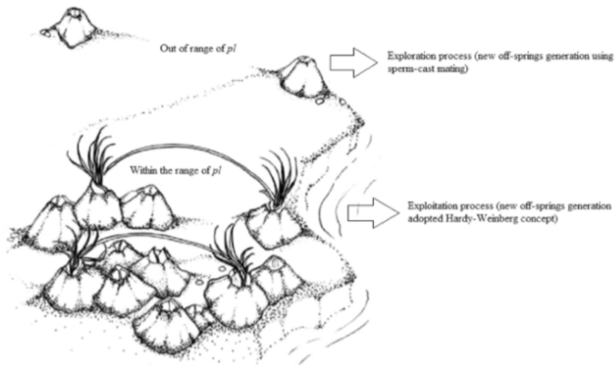

Fig. 3. Exploitation and exploration concept of BMO adopted from [28]

This is done by releasing the fertilized eggs into the water. This exclusive behavior of barnacles in producing new off-springs becoming an insight in the introduction of BMO for solving optimization problems. Figure 4 and 5 show the pseudo code for BMO and Hardy-Weinberg proportions for two alleles, respectively.

```
Initialize the population of barnacles
Set the maximum number of iterations
Initialize the current iteration counter
while current iteration < maximum iterations do:
    for each barnacle in the population do:
        Determine the range of the barnacle's penis
        if range of penis < threshold:
            Perform normal copulation:
                Select a mate barnacle for copulation
                Apply Hardy-Weinberg principle to generate offspring
        else:
            Perform sperm-cast mating:
Release fertilized eggs into the water to generate offspring
        Evaluate the fitness of the generated offspring
        Apply any necessary constraints or selection criteria
    Increment the current iteration counter
end while
Return the best solution found by the barnacles
```

Fig. 4. Pseudo code for BMO

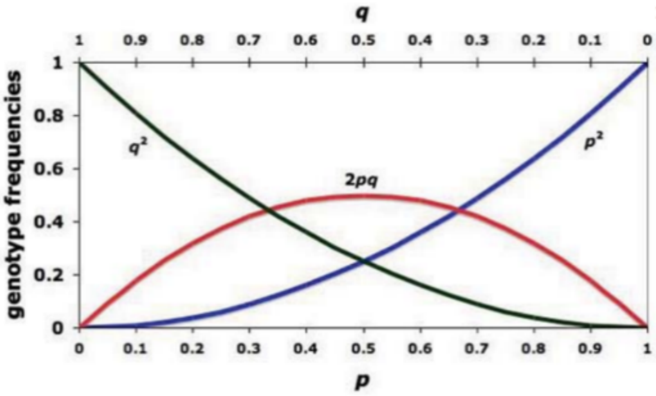

Fig. 5. Hardy-Weinberg proportions for two alleles [28]

To generate the new off-springs of barnacles, Hardy-Weinberg principle is used for normal mating of barnacles. Basically, in the algorithm development, how the barnacle copulated is not to be considered. Only the effect of the barnacle's penis to find the mating is adopted in this algorithm where the range of the penis will determine whether the new off-springs will be generated using Hardy-Weinberg principle or using sperm-cast mating as mention in articles [38]. This method has been applied to find the optimal placement and sizing of FACTS devices for optimal power flow and chiller loading solution for energy conservation [39,40].

3.2 Grey Wolf Optimization (GWO)

The Grey Wolf Optimizer is derived by leadership hierarchy (as shown in Figure 6) and hunting of grey wolf [41]. The dominant social hierarchy of grey wolf have average group of 5-12 members.

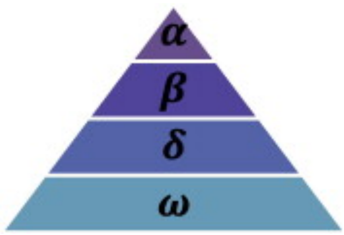

Fig. 6. Hunting hierarchy of the Grey Wolf [37]

The first tier called alpha (α) which dominating the group and responsible for decisions making as a leader. The dominant alpha is selected based on ability to manage their group members well. The next tier is called beta (β) role as assistance to alpha in order to enforce any instruction or command by the leader. Beta could be the next leader with good discipline criteria which can be either male or female.

Delta (δ) is once used to be beta and alpha would be placed on the third-tier roles as hunters, caretakers to the younger members, sentinels and scouts. Hunters help foods delivering to the group members. Caretakers take care of the weak, ill and wounded young members. Sentinels control the security of the members and guarantee their territory safety and scouts role as territory marker to monitor the boundaries and discover any dangers ahead.

The bottom ranking is Omega (ω). Omega appears to be a balance to the nature bio-chain of the grey wolf. Even though their existence is not really appreciated by the other members of the group but still their role as a babysitter to the group can be acceptable. They are last wolves that are permitted to eat the prey.

In grey wolf community, the hunting activity is categorized by three phases as follows:

- Tracking: trace the location of the prey.
- Encircling: trap the prey in a circle.
- Attacking: move towards the prey by fulfilling the terms.

Alpha will lead during the hunting activities as the best solution, followed by Beta as second best and Delta as the third best. Omega will update positions as remaining solution by considering the position of the first, second and third best of the group. The random position within the search area is updated according to the first three best solutions. The estimated position of the prey by alpha, beta and delta will then be a guide to omegas to update their positions. This GWO method has reported in IoT-enabled networks to ensemble feature selection framework for cyber threat detection [42] and in overcurrent relay protection coordination problem [43,44]. Figure 7 shows the pseudo code for Grey Wolf Optimizer.

```
Initialize the population of grey wolves
Initialize the positions of alpha, beta, and delta wolves
Set the maximum number of iterations
Initialize the current iteration counter
while current iteration < maximum iterations do:
  for each wolf in the population do:
    Update the position of the wolf based on the following equations:
      a = 2 - current iteration * (2 / maximum iterations)
      r1 = random number between 0 and 1
      r2 = random number between 0 and 1
      if r1 < 0.5:
        update position using equation (alpha position - current wolf position) * a
      else if r1 >= 0.5 and r2 < 0.5:
        update position using equation (beta position - current wolf position) * a
      else:
        update position using equation (delta position - current wolf position) * a
    Apply boundary constraints to the updated position of the wolf
    Evaluate the fitness of the updated position
  Update alpha, beta, and delta positions based on the best fitness values
  Increment the current iteration counter
end while
Return the best position and fitness found by the grey wolves
```

Fig. 7. Pseudo code for Grey Wolf Optimizer

3.3 Moth-Flame Optimizer (MFO)

MFO algorithm is a nature-inspired meta-heuristic optimization algorithm developed by Seyedali Mirjalili [36]. It is being proven to be competitive with other renowned optimization algorithms as stated in Mirjalili's paper. Moths are insects which are closely related to the butterflies' family. During their lifetime, they generally undergo two main milestones: larvae and adult stages. The inspiration of MFO algorithm is the unique navigation technique of moths at night time. The moths utilized a mechanism known as transverse orientation when navigate at night depending on the moonlight. They fly by retaining their position at a fixed angle with respect to the moon. In nature, the moon is relatively far away from the moths and the moths are actually travelling in a straight line using transverse orientation. Therefore, this mechanism only helpful and useful for travelling in straight line when the source of light is extremely far. However, the moths in fact are mostly tricked by man-made light sources and fly spirally around the lights. In addition, the moths also try to retain the similar angle with respect to the artificial light source.

Nevertheless, this behavior causes deadly spiral fly path for them as the light source is extremely close compared to the moon. The natural behavior of the spiral flying path of moths is shown in Figure 8.

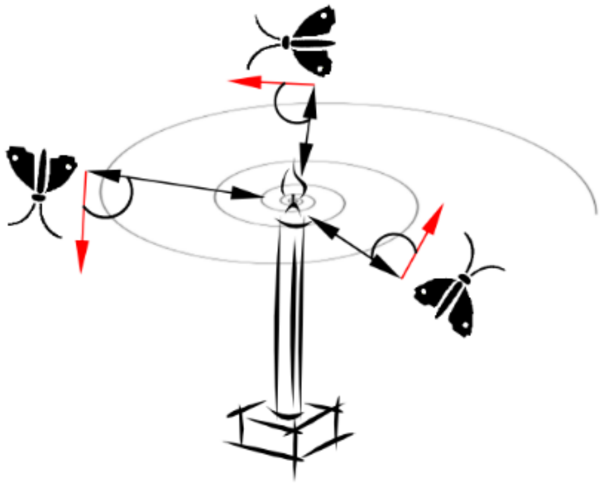

Fig. 8. Moth-Flame's spiral flying path around close light sources

Figure 9 shows the pseudo code for MFO. MFO algorithm has been applied to solve the automatic generation control (AGC), feature selection approach based and others challenging constrained engineering optimization problems [45]. This method has been applied to find the optimal placement and sizing of FACTS devices for optimal power flow and power transmission and distribution [46].

```
Initialize the population of moths
Set the maximum number of iterations
Initialize the current iteration counter
while current iteration < maximum iterations do:
  Calculate the fitness of each moths in the population
  Determine the distance to the best moth in the population
  Update the position of each moth based on the following rules:
    For each moth:
      Calculate the distance to the best moth
      Update the position using the formula:
        newPosition = currentPosition + randomValue * (bestMothPosition - currentPosition)
      Apply boundary constraints to the updated position of the moth
  Evaluate the fitness of the updated moths
  Calculate the light intensity for each moth based on its fitness
  Sort the moths based on light intensity in descending order
  Update the position of the moths based on the sorted order:
    For each moth:
      Update the position using the formula:
        newPosition = currentPosition + randomValue * (bestMothPosition - currentPosition)
      Apply boundary constraints to the updated position of the moth
  Increment the current iteration counter
```

Fig. 9. Pseudo code for MFO

3.4 Ant Lion Optimizer (ALO)

ALO is first developed by Seyedali Mirjalili in the year 2015 [47]. It is inspired by the foraging mechanism of antlions in catching preys. ALO is developed based upon five main stages: random walk of ants, entrapment of ants, building traps, catching preys and rebuilding traps. Firstly, the inspiration of ALO will be discussed followed by the mathematical modelling of ALO.

The name of antlions is initiated by their hunting behavior and their preferably prey (ant). Antlions are insects that belong to the family of Myrmeleontidae and they undergo two main lifecycles: larvae and adult. Their hunting period mostly occurs during larvae and adult stages with the purpose for reproduction. During hunting, an antlion digs a cone-shaped trap and hides underneath the bottom of the trap, as shown in Figure 10.

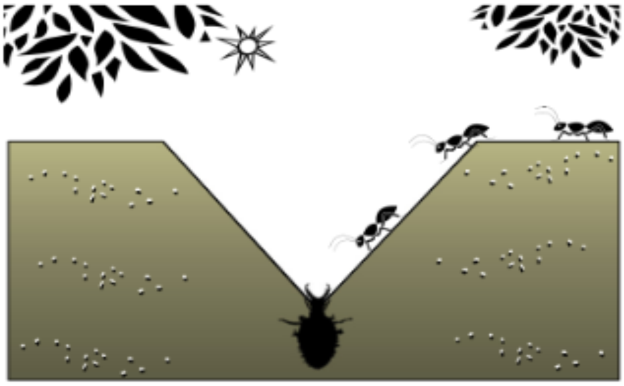

Fig. 10. Hunting behavior of antlions with cone-shaped traps

They are waiting for preys to be trapped in the trap. Once the prey is in the trap, the antlion will throw sand outward the trap to slide the prey toward it. The prey is pulled under the sand and the antlion consumed it. Then, the antlion rebuilds the trap and waiting for the next hunt. Figure 11 shows the pseudo code for ALO. ALO algorithm has been widely implemented to solve the power system and power distribution problem such as load frequency control, sizing of renewable distributed generation and loss reduction in power distribution system [48] and Optimum design of truss structures with discrete variables [49].

```
Initialize the population of antlions
Set the maximum number of iterations
Initialize the current iteration counter
while current iteration < maximum iterations do:
  Calculate the fitness of each antlion in the population
  Calculate the attractiveness of each antlion based on their fitness
  Update the positions of the antlions based on the following rules:
    For each antlion:
      if antlion is the best (highest fitness) in the population:
        Move randomly within the search space
      else:
        Calculate the distance to the antlion with the highest fitness
        Move towards the antlion with a probability based on its attractiveness
      Apply boundary constraints to the updated position of the antlion
  Increment the current iteration counter
end while
```

Fig. 11. Pseudo code for ALO

3.5 Particles Swarm Optimizer (PSO)

Particle swarm optimization (PSO) is introduced by [50] based on the group behavior of animals such as flocking of birds, swarm of bees and school of fish. PSO has similarities with others evolutionary computation algorithm such as GA. The algorithm is initiated with a random solution of the population and explore for optimal solution by regenerating new generations. However, PSO is modest towards GA as it has no crossover and mutation operator. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Compared to GA, PSO has memory as a knowledge of potential solutions stored by the particles and shared the information among them. Whereas in GA, the parent solution is destroyed once the 'child' is generated if the child is better compared to the parent. This special capability of PSO could attract interest from researchers to be implemented in the various optimization problems [51]. Since PSO has no complex operators of mutation and crossover, this could be advantages for PSO to be implemented with fewer parameter adjustment. PSO is used for problems where the objective function is non-linearly parameters. This method has been applied for estimating transmission line parameters based on various scenarios [46] . Throughout the execution of PSO, the particles cooperate and explore the search space, using their own experience (pbest) and the shared information from the swarm (gbest) to guide their search towards the optimal solution. It is important to note that the specific implementation of PSO may vary depending on the problem and the algorithm parameters chosen. The selection of appropriate parameter values is crucial for the convergence and performance of the algorithm. Figure 12 shows the pseudo code for PSO.

```
Initialize swarm of particles
Initialize global best position and fitness
Initialize personal best position and fitness for each particle

while termination condition not met do:
  for each particle in swarm do:
    Update particle velocity
    Update particle position
    Evaluate fitness of particle
    Update personal best position and fitness if necessary
    Update global best position and fitness if necessary
  end for
end while
Return global best position as the optimal solution
```

Fig. 12. Pseudo code for PSO

4. Algorithms with Penalty Function Method

In general, the implementation of metaheuristic algorithm to solve the OCRC problem can be simplified as flowchart in Figure 13 below:

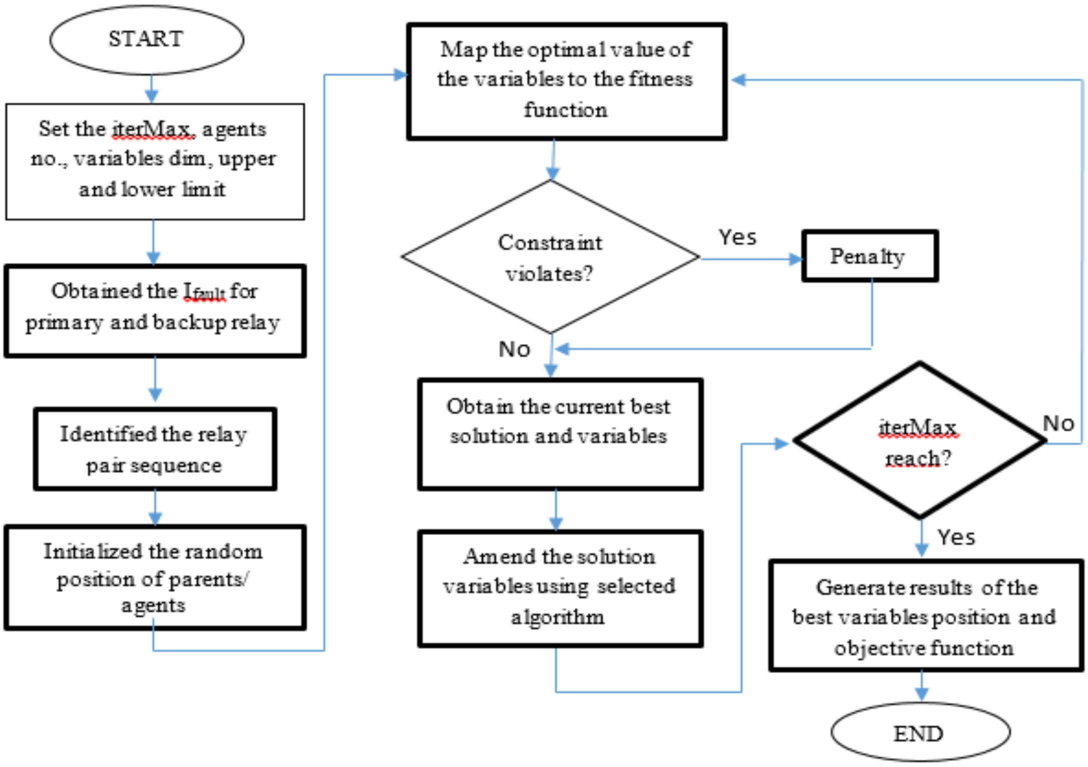

Fig. 13. Implementation of metaheuristic algorithm to solve overcurrent relay coordination problem

Relay coordination problem is one of the optimization problems that came with complex inequality constraints. In this work, relay coordination problem has been formulated as a mix-integer nonlinear programming model. The overcurrent relays coordination problem has several inequality constraints which have been discussed in the earlier problem formulation. These constraints shall be fulfilled by the algorithm in order to find the optimal value of the TMS and PS variables. Optimal value of TMS and PS is then resulted to optimization of the fitness function.

Several techniques have been introduced by the researches to satisfy the complex constraints of relay coordination problem. Death penalty function has been introduced in [52]. This popular method will automatically reject the unfeasible agents from the population. Random search method [53] or also known as direct-method which suitable for discrete and/or continuous variables. In [54], Karush-Kuhn-Tucker method is applied for any violating to the margin of the variables or time coordination constraint in order to get the optimal results. However, some of the researches did not mention at all on how they are dealing with the inequality constraints on overcurrent relays coordination problem.

Penalty function method has been chosen together with the algorithm [37] to avoid the violated agents is selected in the next iterations. The objective of penalty functions is to transform the constrained problems into unconstrained problems by presenting an artificial penalty for violating the constraint [55]. If any of the constraints is violated, a large penalty is invoked to supersede the violated agents for the next iteration. The violated agents are replaced with the new agents for positioning update. On the other hand, the penalty is equal to zero if all constraints are satisfied and the same agents is taken into account for the next iteration. Furthermore, in MATLAB programming, the penalty factor has often been assigned a big value. The search agents/ offsprings re-positioning their location by referring to the updated location of the new agents/ offsprings. The agents/offsprings will be superseded in next iteration if any of the constraints is violated and replaced with the new agents/ offsprings. They will be given penalty so in the next iteration, the same superseded agents will not be selected. The above issue can be formulated by Eq. (13).

$$F = F_x + k \sum_{i=N_{CTI}^{\lim}}^{m} \lambda_{CTI} \tag{13}$$

F is the fitness function comprises of objective function and penalty function terms, where *F_X* is the objective function. $N_{CTI}^{\lim}$ represents the set of relays violating the CTI limits. In addition, *m* is the number of related relays, *k* is the penalty factor whereas λ_{CTI} are the sum of relays CTI value that are given penalty.

5. Results and Discussions

Simulations was conducted to demonstrate the efficiency of the proposed methods of BMO, GWO, ALO, MFO & PSO techniques based on three test cases from IEEE test bus. The simulations were conducted by using MATLAB software and executed on an intel core i5-6200U CPU, 2.3GHz with 8GB RAM. The normal inverse (NI) characteristic curve has been chosen to be applied during the simulation which represented the normal condition of the system without considering any special needs. The priority factors to established the superiority of an algorithm are the minimum value of objective function with less or without constraint violation will be crowned as the most efficient and reliable method.

5.1 98: IEEE 3 Bus Test System

The IEEE 3-bus test system is powered by 69kV system voltage with three generators rating 100MVA with 20% reactance, 25MVA with 12% reactance and 50MVA with 18% reactance respectively. The system consists of three busbar (B_1, B_2 and B_3), three ring lines and six overcurrent relay (R_1, R_2, R_3, R_4, R_5 and R_6). The schematic diagram of the system as in Figure 14.

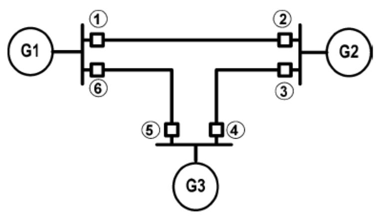

Fig. 14. IEEE three bus test system

The Line data as in Table 2 and current transformer (CT) ratio in Table 3 for the 3-bus test system. The TMS variables are bound from X_1 to X_6 and PS variables are bound from X_7 to X_{12}

Table 2
Line data for three bus test system

Line no.	Length (km)	Line impedance, Z
Line 12	50	5.5+j22.85Ω
Line 23	40	4.4+j18.00Ω
Line 13	60	7.6+j27.00Ω

Table 3
CT ratio for three bus test system

Relay no.	CT Ratio
1	300/5
2	200/5
3	200/5
4	300/5
5	200/5
6	400/5

For case 1, the results are presented in nonlinear mixed-integer with continuous TMS and continuous PS models. The maximum iteration no. is 1000 and search agents is 40 are implemented to all algorithms. The TMS variables are varies from 0.1 to 1.1 seconds whereas the PS variables varies from 0.3 to 1 of the current transformer ratios. The CTI value applied to this simulation test case is 0.3 seconds. The result in Table 4 shows that the MFO outperformed other algorithms with objective function of 1.4779 seconds and the second-best results is GWO with 1.4784 seconds. The different in between ALO and GWO is 0.0005 seconds. Whereas the worst result is obtained by BMO with 1.8602 seconds which 25.8% more than ALO.

Table 4
Optimal setting of ALO, MFO, GWO, BMO and PSO for three bus test system

Relay no.	ALO		MFO		GWO		BMO		PSO	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	1.5000	0.1000	1.5000	0.1000	1.5018	0.1000	1.5000	0.1000	1.5000
2	0.1000	2.6080	0.1000	2.6080	0.1000	2.6120	0.1741	1.5000	0.1000	2.6079
3	0.1000	2.9749	0.1000	2.9749	0.1000	2.9763	0.1953	1.5000	0.1000	2.9748
4	0.1000	1.5837	0.1000	1.5837	0.1000	1.5848	0.1000	1.5837	0.1000	1.5837
5	0.1000	2.8134	0.1000	2.8134	0.1000	2.8173	0.1880	1.5000	0.1000	2.8134
6	0.1000	1.5000	0.1000	1.5000	0.1000	1.5007	0.1000	1.5000	0.1000	1.5000
Objective function (s)	1.4879		1.4779		1.4784		1.8602		1.4824	

Figure 15 projects the best, median and worst objective function for case 1. The GWO starts with the highest objective function but ended at the second place lowest best objective function whereas MFO starts low and ended as first place for lowest best. The convergence graph in Figure 16 shows that MFO converged smoothly and became stable at 100 iterations compared to the other algorithms which converged faster and resulted to higher relay operating time. It is good to converge at the earliest point; however, this condition could possibly trap in local minima which there is no global minimum are found. However, it could be concluded that all algorithms converged within 100 iterations. In addition, there are no violation of constraints are reported for all the algorithms. It is worth to highlight that, MFO is the most efficient and reliable algorithm for the case 1.

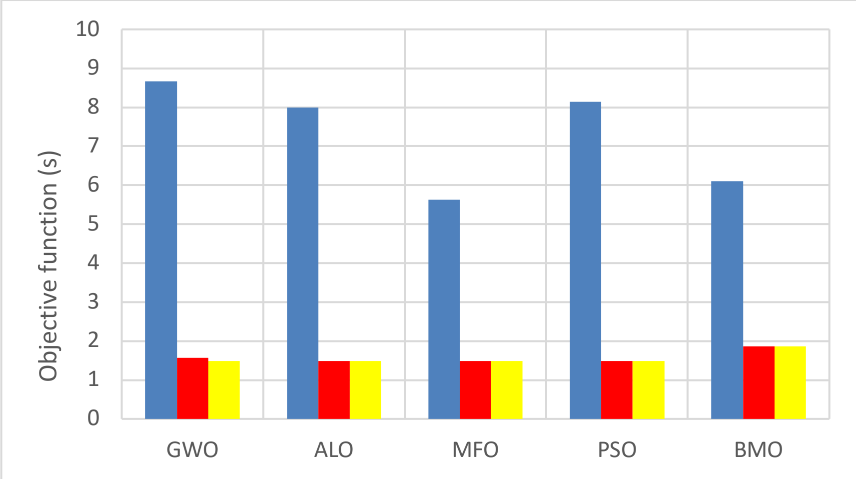

Fig. 15. The best, median and worst objective function for case 1

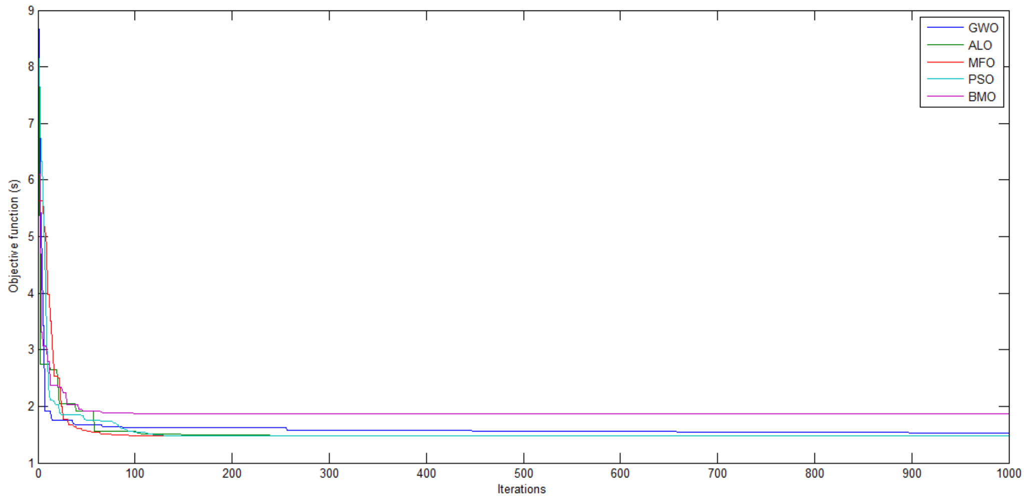

Fig. 16. Convergence curve for GWO, ALO, MFO, PSO and BMO algorithm for case 1

5.2 Case 2: IEEE 8 Bus Test System

The IEEE 8 bus test system schematic diagram as in Figure 17 which has a link to a neighbourhood network, modelled by a short circuit power of 400MVA. The system is powered by 10kV system voltage with two generators at node 7 and 8 which consist of eight busbars (B_1, B_2.... B_8) with seven ring lines and 14 overcurrent relays (R_1, R_2…R_{14}). The generators', lines and transformer's data are as in Table 5, Table 6 and Table 7, respectively. The current transformer ratio of the relays *R3, R7, R9, R14* are assumed as 800:5 and relays *R1, R2, R4, R5, R6, R8, R10, R11, R12, R13* are 1200:5. The variables dimension is 28. The variables bound from X_1 to X_{14} for TMS and PS bound from X_{15} to X_{28}. The short circuit value of the system is represented in Table 8.

Table 5
Generator data for IEEE eight bus test system

Node	Sn (MVA)	Vp(kV)	Vs(kV)	Reactance (%)
7-1	150	10	150	4
8-6	150	10	150	4

Table 6
Line characteristic for IEEE eight bus test system

Node	Sn (MVA)	Vp(kV)	Reactance (%)
7	150	10	15
8	150	10	15

Table 7
Transformer data for IEEE eight bus test system

Nodes	R (Ω/km)	X (Ω/km)	Y (S/km)	Length (km)
1-2	0.004	0.0500	0.0	100
1-3	0.0057	0.0714	0.0	70
3-4	0.0050	0.0563	0.0	80
4-5	0.0050	0.0450	0.0	100
5-6	0.0045	0.0409	0.0	110
2-6	0.0044	0.0500	0.0	90
1-6	0.0050	0.0500	0.0	100

Table 8
Near end 3ϕ short circuit for 8 bus test system [51]

Primary relay	I (A)	Backup relay	I (A)
1	3232	6	3223
2	5924	7	1890
3	3556	2	3556
4	3783	3	2244
5	2401	4	2401
6	6109	14	1847
7	5223	5	1197
8	6093	7	1890
9	2484	10	2484
10	3883	11	2344
11	3707	12	3707
12	5899	14	1874
13	2991	8	2991
14	5199	1	996

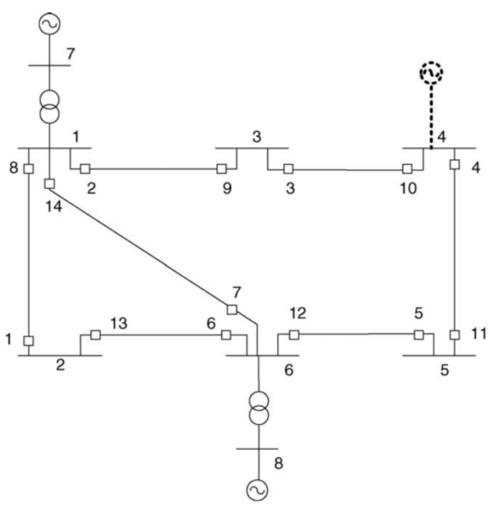

Fig. 17. IEEE eight bus test system [51]

In Case 2, where IEEE 8 bus test system is chosen with the maximum iteration no. is 1000 and search agents is 40 are implemented for all algorithms. In addition, the TMS boundary limit is continuous from 0.1 to 1.1 seconds and PS boundary is continuous from 1.5 to 5 with the consideration of CTI value is 0.3 seconds. For a bigger test system BMOs has shown better performance in terms of total operating time which has outperform the other algorithms with 7.9598 seconds in Table 9. The worst result is PSO with 10.0679 seconds which 2.1081 seconds or 26.4% more than BMO. The PSO is the fastest algorithm that converged below than 10 iterations and could possibly trap in local minima which resulted to the worst results generated with no global minimum are found. Moreover, PSO has highest numbers of relays pair that violated the CTI constraint where the CTI values recorded are less than 0.3 seconds compared to the other algorithms. This condition might lead to the malfunction trips event to the system. This conflict may be addressed due to the short circuit values that are same for the primary and back-up relays pair. As shown in Figure 19, BMO starts low and ended at the 1st place as the lowest best objective function for case 2. BMO converged at more than 50 iterations which among the slowest algorithm to converge towards the best results and become steady at 200 iterations as in Figure 18.

Table 9
Optimal setting of ALO, MFO, GWO, BMO and PSO for 15 bus test system

Relay no.	ALO		MFO		GWO		PSO		BMO	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	1.9773	0.1000	1.5000	0.1018	1.5000	0.1021	1.5783	0.1000	1.5000
2	0.3359	1.5012	0.3362	1.5000	0.1106	4.0000	0.1000	4.2314	0.1000	4.3734
3	0.4888	2.0931	0.1713	5.0000	0.1717	5.0000	0.1713	4.9330	0.1713	5.000
4	0.7147	3.6785	0.4346	5.0000	0.4348	5.0000	0.5213	5.000	0.4345	5.0000
5	0.1000	1.5003	0.1000	1.5000	0.1009	1.5000	0.1000	1.6301	0.1000	1.5000
6	0.1000	1.5000	0.1000	1.5000	0.1002	4.0000	0.1000	1.5000	0.1000	1.5000
7	0.1000	1.5000	0.1000	1.5000	0.1003	3.0000	0.1000	1.3490	0.1000	1.5000
8	0.1000	1.6083	0.1000	4.3143	0.1007	4.5000	0.1000	4.2130	0.1000	4.3143
9	0.1000	1.5152	0.1000	5.000	0.1002	5.0000	0.1000	4.6530	0.1000	5.0000
10	0.1000	1.5647	0.3784	1.5000	0.1004	4.0000	0.1000	4.9780	0.1000	4.1254
11	0.1000	1.5000	0.1000	1.5000	0.1059	1.5000	0.1000	2.0123	0.1000	1.5000
12	0.1000	1.5420	0.1000	1.5000	0.1003	4.5000	0.1000	1.5000	0.1000	1.5000
13	0.1000	1.5004	0.1000	1.5000	0.1006	1.5000	0.1000	1.7900	0.1000	1.5000
14	0.1000	1.9899	0.1000	5.0000	0.1013	2.0000	0.1000	2.5045	0.1000	2.0562

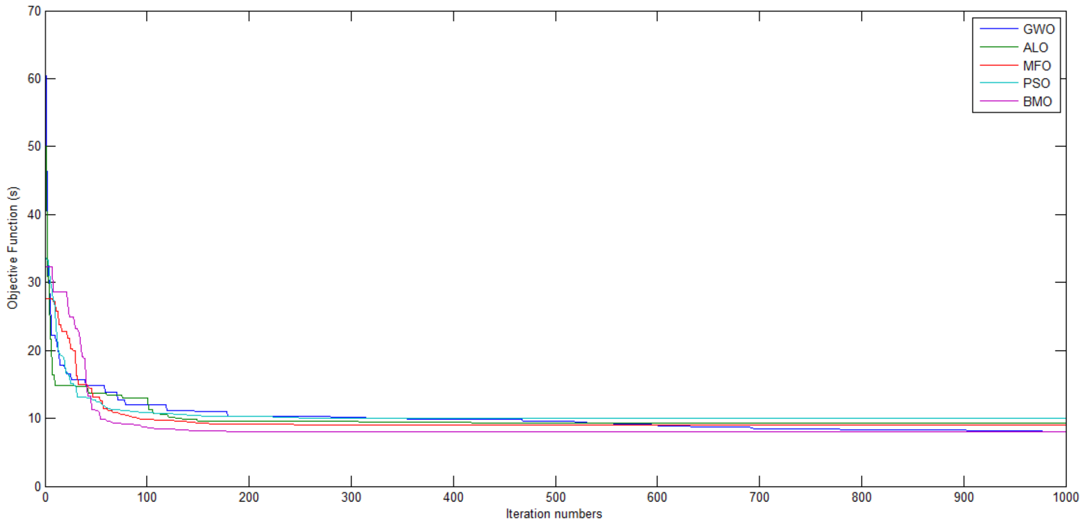

Fig. 18. Convergence curve for GWO, ALO, MFO, PSO and BMO algorithm for case 2

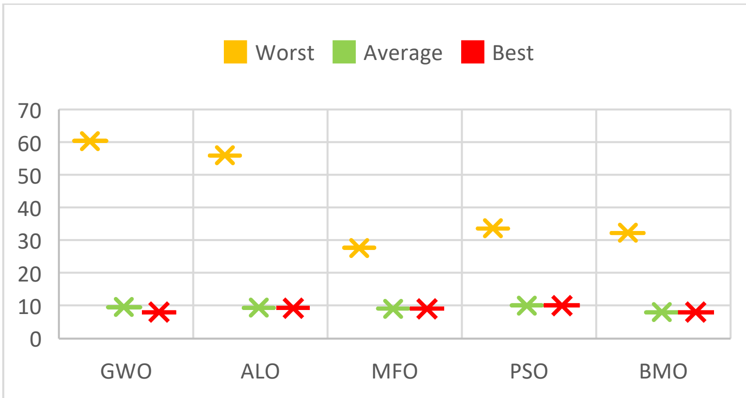

Fig. 19. Worst, average and best objective function for case 2

5.3 Case 1: IEEE 15 Bus Test System

The IEEE 15-bus test network is a highly DG penetrated distribution network with an external grid. The DGs are penetrated at six bus location of B1, B3, B4, B6, B13 and B15 as shown in Figure 20 and CT ratio as in Table 10. Each generator has a synchronous reactance 15% with 15 MVA and 20-kV ratings. The external grid has 200-MVA short circuit capacity. The reactance of each line section is *Z=0.19+j0.46Ω/km*. The detail system's data and short-circuit analysis for near-end 3Φ faults based on the IEC standard are given in [32]. The test case has 42 relays and 21 lines with the variables dimension are 84. The TMS variables are bound from X_1 to X_{42} and PS variables are bound from X_{43} to X_{84}. The normal inverse type characteristic is selected. The TMS values is in between greater than 0.1 seconds and the PS value is in between 1.5 to 5. The CTI value is assumed as 0.2 seconds. The system details on three phase short circuit data can be found in [4]. The constant values used are according to IEC standard [31] which Case 1 implemented normal inverse (NI) with k = 0.14 and α = 0.02.

Table 10
CT ratio for IEEE 15 bus test system

Relay no.	CT ratio
18-20-21-29	1600/5
2-4-8-11-12-14-15-23	1200/5
1-3-5-10-13-19-36-37-40-42	800/5
6-7-9-16-24-25-26-27-28-31-32-33-35	600/5
17-22-30-34-38-39-41	400/5

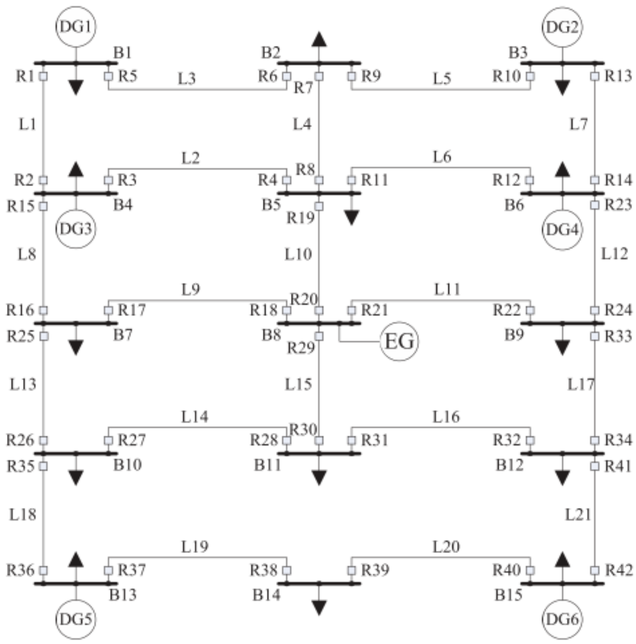

Fig. 20. IEEE 15 bus test system [56]

During simulation, Figure 21 shows GWO generated the best results for case 3, with 12.7336 seconds' total operating time. The superiority of GWO towards the ALO, MFO, PSO and BMO is about 40%, 32.5%, 46% and 61% respectively. GWO has greater ability in handling bigger test cases as compared to ALO, MFO, PSO and BMO. This has evidenced the flexibility and efficiency of the GWO method compared to the other algorithms. From the convergence curve in Figure 22, BMO converged too fast which resulted to the worst outcome compared to the others. On the other hands, GWO gradually converged towards the 1000 iterations. This pictured that GWO needs higher iterations number as compared to the other algorithms but gave better results. Moreover, the computational time of the GWO is still adequate and acceptable even though the number of iterations is high. So, it is worth to emphasize that GWO has the ability to coordinate overcurrent relays in a mesh power distribution network and at the same time complying all the mandatory constraints. The optimal setting of ALO, MFO, GWO, BMO and PSO for three bus test system is tabulated in Table 11.

Table 11
Optimal setting of ALO, MFO, GWO, BMO and PSO for three bus test system

Relay no.	ALO		MFO		GWO		PSO		BMO	
	TMS	PS	TMS	PS	TMS	PS	TMS	PS	TMS	PS
1	0.1000	1.5000	0.1000	5.0000	0.1013	2.7320	0.1001	2.7543	0.2742	1.7247
2	0.1041	1.5002	0.1000	5.0000	0.1001	1.7947	0.1000	1.5000	0.1000	3.5443
3	0.1153	2.6638	0.1000	1.5000	0.1002	1.5621	0.1000	1.5000	0.1000	1.5000

4	0.1675	1.8093	0.1000	5.0000	0.1018	2.6221	0.1234	2.2647	0.3133	1.5000
5	0.1227	1.5305	0.1000	1.5000	0.1083	1.5487	0.1000	1.5000	0.1000	1.5000
6	0.1035	1.6381	0.1000	1.5000	0.1002	1.5042	0.1000	1.5001	0.1167	1.8389
7	0.1501	1.5000	0.1000	5.0000	0.1013	2.1928	0.1085	2.0801	0.1552	2.4225
8	0.1633	1.5002	0.1572	1.5607	0.1001	2.5192	0.1025	2.3438	0.1299	3.2253
9	0.1338	1.5029	0.1000	2.0116	0.1004	2.0425	0.1000	2.0366	0.2136	1.5000
10	0.1608	1.5000	0.1000	1.5000	0.1003	1.7860	0.1028	1.5000	0.1042	1.5000
11	0.1522	1.7333	0.1000	5.0000	0.1000	2.5195	0.1435	1.8555	0.1069	4.9607
12	0.1920	1.5978	0.1000	2.8086	0.1012	2.8016	0.1000	2.8365	0.1000	4.0355
13	0.1347	1.5448	0.1386	1.5000	0.1003	2.7715	0.1002	2.0730	0.2271	1.5000
14	0.1000	1.5219	0.1000	1.5000	0.1033	1.6329	0.1005	1.5000	0.1000	2.3828
15	0.1000	1.5005	0.1000	1.5000	0.1011	1.6711	0.1001	1.5000	0.1208	1.5000
16	0.1000	1.5114	0.1000	1.5000	0.1007	1.5035	0.1000	1.5003	0.1000	1.5000
17	0.1791	1.5000	0.1000	1.5000	0.1003	1.9094	0.1005	3.0662	0.2769	1.5000
18	0.1219	1.6402	0.1000	5.0000	0.1003	2.0602	0.1023	3.9165	0.1000	5.0000
19	0.1365	1.5000	0.1000	2.0509	0.1001	2.1253	0.1013	2.0517	0.2158	1.5000
20	0.1295	2.0075	0.1000	1.6165	0.1002	1.6312	0.1000	1.6381	0.1772	1.5000
21	0.1245	1.5022	0.1000	1.5504	0.1001	2.4752	0.1005	1.5636	0.1000	3.8806
22	0.1002	1.5000	0.1000	1.5000	0.1007	1.5455	0.1002	1.5011	0.1000	1.5000
23	0.1000	2.6459	0.1000	1.5000	0.1016	1.5723	0.1000	1.5000	0.2127	1.5000
24	0.1636	1.7246	0.1000	1.5000	0.1000	1.5245	0.1001	1.5000	0.1000	1.5000
25	0.1000	1.5002	0.1000	1.5000	0.1001	1.5056	0.1000	1.5000	0.1000	1.7591
26	0.2524	1.5000	0.1217	2.4757	0.1002	3.1433	0.1043	2.8275	0.3660	1.5000
27	0.1384	1.5541	0.1000	1.9831	0.1057	1.9240	0.1000	2.0065	0.2324	1.5000
28	0.1002	1.6536	0.1000	1.5000	0.1007	1.5607	0.1000	1.5000	0.1509	1.5000
29	0.1161	1.7953	0.1000	1.5536	0.1071	1.6619	0.1000	1.5750	0.1000	4.9977
30	0.1000	2.1464	0.1000	2.1238	0.1001	2.1626	0.1000	2.1493	0.1685	2.0983
31	0.1344	1.5009	0.1345	1.5000	0.1119	1.8264	0.1030	1.9844	0.3385	1.5000
32	0.2203	1.5124	0.1000	2.9982	0.1005	2.9962	0.2250	1.5007	0.1000	4.9917
33	0.1000	1.5006	0.1000	1.5000	0.1000	1.5108	0.1000	1.5000	0.1000	1.5000
34	0.1045	1.5000	0.1000	1.5000	0.1006	1.9720	0.1000	1.5000	0.1509	1.5000
35	0.1976	1.5000	0.1000	1.9328	0.1000	2.0547	0.1005	1.9470	0.2101	1.5000
36	0.1000	1.5001	0.1000	5.0000	0.1003	3.3072	0.1082	3.1402	0.2645	2.2710
37	0.119	1.5053	0.1000	5.0000	0.1034	2.0512	0.1000	1.7994	0.2111	1.5000
38	0.1789	1.5001	0.1000	5.0000	0.1009	2.4801	0.1507	1.7733	0.2113	1.9199
39	0.1136	2.2953	0.1000	5.0000	0.1086	2.3918	0.1001	2.5756	0.1000	3.5146
40	0.1835	1.5031	0.1000	2.5449	0.1001	2.6924	0.1750	1.5421	0.2848	1.5000
41	0.1000	1.5000	1.1000	1.5000	0.1007	1.5155	0.1000	1.5000	0.1580	1.5000
42	0.1000	1.5245	0.1000	5.0000	0.1001	3.6070	0.1006	3.3994	0.1000	4.6698

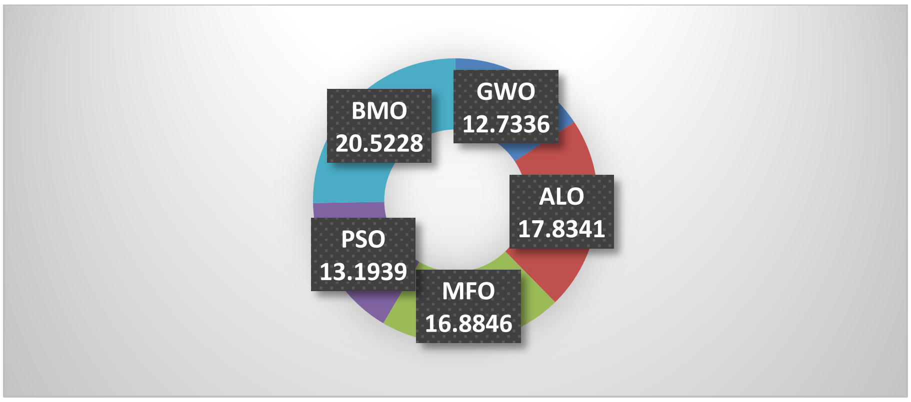

Fig. 21. Best objective function (seconds) for 15 bus test system

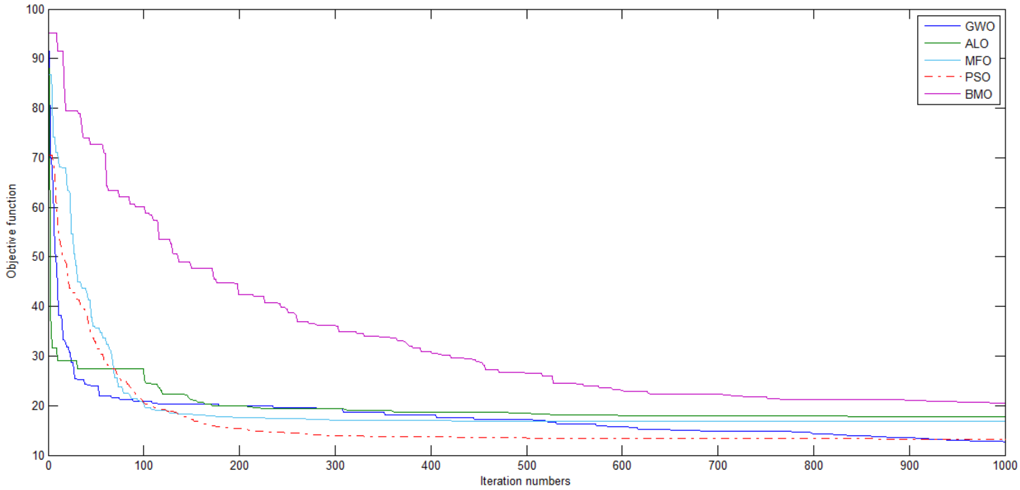

Fig. 22. Convergence curve for GWO, ALO, MFO, PSO and BMO algorithm for case 3

6. Conclusion

This article investigated five metaheuristic algorithms to solve the overcurrent relay coordination problem. The algorithms called ALO, MFO, GWO, PSO and BMO have been simulated using the normal inverse (NI) characteristic curve. Comparative analysis shows that MFO is able to outperformed the others algorithm for small scale of distribution system as Case 1. For bigger test case as Case 2, BMO shows efficient results for which total operating time is ahead than the other algorithms with lesser constraints violation. On the other hand, GWO shows greatest test results for mesh power distribution network of Case 3. The convergence slope gradually decreases within sufficient and acceptable computational time and earn good points in terms of reliability, efficiency and flexibility attributes. Hence, this investigation study could establish another alternative method of solving the overcurrent relay coordination problem.

Competing Interests and Acknowledgement
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