

Article

# Optimal Allocation of Distributed Generation Using Improved Cuckoo Search Algorithm

Adamu Shehu Timta<sup>1,\*</sup>, Mohammed Buba Umar<sup>1</sup>, Ahmed Shehu Timta<sup>1</sup>, Matthew Iyobhebhe<sup>2</sup>, and Paul Thomas Muge<sup>3</sup>

<sup>1</sup> Department of Electronics and Telecommunication Engineering, Ahmadu Bello University Zaria, Kaduna, Nigeria

<sup>2</sup> Department of Electrical/Electronic Engineering, Federal Polytechnic Nasarawa, Nigeria

<sup>3</sup> Department of Electrical Engineering, Federal Polytechnic Nyak Shendam, Plateau, Nigeria

\* Correspondence: Adamu Shehu Timta ([adamutimta@yahoo.com](mailto:adamutimta@yahoo.com))

**Abstract:** This work presents an improved cuckoo search algorithm based on Success Rate (CSA-SR) for optimal allocation of Distributed Generation (DG). This is necessary in order to improve the power quality of the distribution system by minimizing power loss and improving voltage stability. Voltage Stability Index (VSI) is applied to identify restricted unhealthy buses/areas in the distribution networks. The work is implemented on standard IEEE 33 Bus test systems. Newton Raphson Power Flow (NRPF) technique is used in MATLAB R2019b environment for the power flow analysis. The overall IEEE 33 Bus system real power loss obtained from the simulation result is found to be 202.7071MW at the base case. Following the application of 3 DGs using CSA-SR, the real power loss is found to be 113.9630 MW which shows a reduction of 88.441MW which is equivalent to 43.77% as related to the base case. The results minimized the system losses while significantly enhancing the voltage profile of the bus voltages as a result of optimal siting and sizing of the DG. These show that the CSA-SR technique outperformed PSO, which was used to ascertain the effectiveness of the developed scheme.

**Keywords:** Cuckoo Search Algorithm, Distributed Generation, 3DGs, Power Loss, Particle Swarm Optimization

## 1. Introduction

Energy demand grows at a faster pace than electricity generation due to continuous growth in population, enhanced industrialization and improvement in living standards [1, 2]. Electricity generation from fossil fuels still remains the main source of energy generation [3]. However, generation of electricity from these sources (oil, gas, coal, etc.) has negative impact on the environment in addition to continuous changes in fuel prices [4, 5]. This has increased the urge of researchers and governments in countries to generate electricity from renewable energy sources [6]. Distributed generation now constitutes a major part of the power systems [7]. Distribution networks are majorly of two types: radial or weekly meshed networks.

The operation of the distribution system (DS) has become a challenging and complex work for the power utilities due to the continual expansion in load demand brought on by the inherent growth of the current system, which results in voltage instability, a rapid increase in power loss, and low power factor. Strategies are now being developed (capacitor placement, dispersed generator placement and network reconfiguration) in order to minimize power losses in the distribution system [6]. Effective location of the DG is needed to ensure system balance, reduction in voltage drop and power loss. To improve the performance of the distribution system, engineers in DISCOS are increasingly incorporating renewable Distributed Generation (DG) technology or Flexible

AC Transmission System (FACTS) components like the Distribution Static Synchronous Compensator (DSTATCOM) into RDS. The problem of DG allocation on RDS has been the subject of extensive investigation. However, careful consideration must be given to the device's optimal placement in order to maximize the technical, financial, and environmental benefits; failing to do so can result in voltage instability, increased system losses, and reverse power flow, all of which pose risks to the operation of the entire system [8]. Therefore, the system's potential benefits are significantly impacted by the device's ideal placement [9]. References [10] and [11] developed an optimal scaling and siting of DG for power quality improvement of the distribution network in Nigeria. The distribution system's operations were investigated, and a sensitivity analysis was created to determine the best location and DG unit size for an unbalanced radial distribution system. Reference [5] conducted research on the effects of adding dispersed generators to the electrical power supply. Distributed generation was included in the DN in order to reduce voltage drop and power losses in the network.

The examined literature makes it clear that methods must yet be developed to make sure DGs in power systems are appropriately sized and located in order to improve power quality. Accordingly, this study provides an enhanced cuckoo search algorithm (CSA) based on success rate for the best DG siting and sizing in order to reduce power loss and

subsequently ensure an improvement in power quality. Similar to this, a measure known as the Voltage Stability Index (VSI) is used to identify unhealthy buses and locations in distribution networks. To determine the effectiveness of the devised approach, the work was tested using the common IEEE 33 Bus test system. The load flow study was conducted using the Newton Raphson Power Flow technique in the MATLAB R2019a environment.

It is clear from the literature review that there is need to effectively size and locate DGs as this will in turn improve the power quality of the systems. As such, this study develops an enhanced cuckoo search algorithm (CSA) based on the success rate for proper DG siting and sizing in order to reduce power loss and subsequently ensure an improvement in power quality. To validate the suggested approach, the work was tested using the common IEEE 33 Bus test system. The load flow study was conducted using the Newton-Raphson Power Flow technique. The results exposed the optimal effects of DG in provisions of technical impacts that minimized the system losses while enhancing the voltage profile of the bus voltages following optimal siting and sizing of the DG. This justifies the contribution of the paper.

## 2. Problem Formulation

The objective function of this research is to minimize power losses and improve the voltage profiles of the distribution network. The objective function  $f$  is described mathematically by (1).

$$\text{Minimize}(f) = \sum_{i=1}^{Nbr} I_i^2 R + \sum_{k=1}^{Nb} V_k - (v_k^{sp})^2 \quad (1)$$

Subject to:

$$V_k \leq V_{kmax} \quad (2)$$

$$0 \leq P_{DG} \leq P_{DG}^{max} \quad (3)$$

$$\leq Q_{DG} \leq Q_{DG}^{max} \quad (4)$$

$$I_i \leq I_i^{max} \quad (5)$$

where,  $I_i$ ,  $I_i^{max}$  and  $R_i$  are the current in  $i$ th branch, thermal limit of  $i$ th branch and resistance of the system respectively.  $V_k$  is the voltage at  $k$ th bus and  $V_{ksp}$  is the specified voltage of  $k$ th bus.  $P_{DG}$ ,  $Q_{DG}$ ,  $P_{DG}^{max}$ ,  $Q_{DG}^{max}$  and  $DG$  depict active DG power injection, reactive DG power injection, maximum allowable active and reactive DG power injections, respectively. Furthermore,  $V_{k,min}$  and  $V_{k,max}$  are the lower and upper voltage limits of  $k$ th bus, respectively whereas  $Nbr$  and  $Nb$  are the number of branches and buses of the system, respectively.

## 3. Cuckoo Search Algorithm

The Cuckoo Search (CS) algorithm is a nature-inspired optimization algorithm that was introduced by Xin-She Yang and Suash Deb in 2009.

Key concepts of the cuckoo search algorithm are [7]:

1. Levy Flight: This behavior is modeled using Levy distribution, which helps the algorithm explore the solution space efficiently.
2. Nest and Egg Representation: In CS, nests represent potential solutions to the optimization problem, and each egg corresponds to a candidate solution within a nest. Cuckoos lay eggs in nests, symbolizing the exploration of the solution space.
3. Objective Function: The fitness or quality of a solution is determined by an objective function, which needs to be minimized or maximized depending on the nature of the optimization problem.

The basic steps of cuckoo search algorithm are [6]:

1. Initialize Population: Initialize a population of nests with random solutions. This represents the initial set of candidate solutions.
2. Evaluate Fitness: Evaluate the fitness of each nest based on the objective function.
3. Levy Flight: Perform a Levy flight to generate new candidate solutions. This step involves random and long-distance explorations to enhance the global search capability.
4. Egg Laying and Replacement: Replace poorly performing nests with new solutions generated through Levy flights. This step is analogous to the idea that cuckoos replace eggs in nests of other birds.
5. Local Search (Optional): Optionally, apply a local search to refine solutions and exploit local information.
6. Termination Criteria: Check for termination criteria (e.g., a maximum number of iterations or achieving a satisfactory solution).

Mathematical representation of levy flight can be accomplished as [1]:

The Levy flight in CS is typically represented using the following equation for updating a solution  $x_i$  at iteration  $t$ :

$$x_i(t+1) = x_i(t) + \alpha \odot Levy \quad (6)$$

where:

- $\odot$  denotes the element-wise multiplication.
- $\alpha$  is a scaling factor.
- $Levy$  is a random vector following the Levy flight distribution.

In summary, Cuckoo Search is a nature-inspired optimization algorithm. It draws inspiration from the breeding behavior of cuckoos. It has been successfully applied to various optimization problems and demonstrates a good balance between exploration and exploitation in the search space.

The success rate of a CSA is generally evaluated based on its ability to find high-quality solutions within a reasonable amount of time, convergence speed, and robustness across different problem types. Assessment of success rates is done using benchmark problems, real-world applications, or mathematical functions that serve as a standard to compare the performance of different optimization algorithms [2].

## 4. Power System Description

### 4.1. Optimal 3 Bus Numbers and Ratings of Generators for 33 Bus System

The selection of optimal bus numbers and generator ratings in a power system is a complex task, involving several factors, i.e., the system's topology, load demand, and operational constraints. Without specific details about the characteristics and requirements of the 33-bus system, one can provide some general considerations and steps that might be involved in determining optimal bus numbers and generator ratings [7]:

#### Optimal Bus Numbers:

1. Analyze the load distribution across the network. Different buses may have different loads, and optimal bus numbers should consider the geographic and load characteristics of the system [3].
2. Consider the connectivity of buses in the system. Identify critical buses.
3. Evaluate the voltage profile of the system. Optimal bus numbers should be selected to maintain voltage levels within acceptable limits and minimize voltage deviations.
4. Take into account any future expansion plans or changes in the network topology.

#### Generator Ratings:

1. Assess the total load demand on the system. Generator ratings should be sufficient to meet the peak and continuous load requirements while considering factors like diversity and load growth.
2. Size generators appropriately based on the diversity of loads, and consider factors such as reactive power requirements, power factor correction, and reserve capacity.
3. Consider operational constraints such as voltage limits, thermal limits, and transient stability. Generator ratings should comply with these constraints to ensure reliable and secure operation.
4. If the system includes renewable energy sources, like wind or solar, generator ratings should be chosen to accommodate the intermittent nature of these sources and maintain grid stability.
5. Assess the economic implications of generator ratings, including the cost of installation, maintenance, and fuel consumption. Optimize the generator ratings to minimize overall operational costs [7].

#### Power Flow Analysis:

1. Conduct load flow studies to analyze the steady-state behavior of the system. This will help in identifying voltage profiles, power flows, and potential issues.
2. Perform contingency analysis to evaluate the system's robustness under various fault scenarios. Ensure that the selected bus numbers and generator ratings can handle contingencies [5].

It should be kept in mind that the specific details of the power system, including the network topology, load characteristics, and other technical and economic considerations, are critical for making accurate decisions. Therefore, the assistance of power system engineers and specialized software tools for power system analysis is often essential to determine the optimal bus numbers and generator ratings for a given system.

### 4.2. Concept of Voltage Stability Index (VSI)

Voltage Stability Index (VSI) assists in identifying areas or buses where the voltage becomes unstable, leading to potential voltage collapse. The voltage collapse can result in widespread power outages and system instability. The VSI is particularly useful for distribution networks, where maintaining voltage stability is crucial. The VSI is typically calculated based on the voltage deviation (VD) from the nominal value and the power injection at a specific bus [8]. The following are the general steps to calculate VSI along with the mathematical equations:

$$VD_i = \frac{V_i - V_{nom}}{V_{nom}} \quad (7)$$

where  $VD_i$  is the voltage deviation at bus,  $V_i$  is the actual voltage magnitude at bus,  $i$ ,  $V_{nom}$  is the nominal voltage magnitude.

Power Injection Sensitivity Factor (PISF) is calculated by

$$PISF_i = \frac{\partial P}{\partial V_i} \quad (8)$$

where  $\partial P/\partial V_i$  and  $PISF_i$  are the partial derivative of power injection with respect to voltage at bus  $i$  and the power injection sensitivity factor at bus  $i$  respectively.

The voltage stability index is the sum of the voltage deviation and the power injection sensitivity factor for each bus. It provides a comprehensive measure of the voltage stability at each bus within the distribution network.

$$VSI_i = PISF_i + VD_i \quad (9)$$

Buses or areas with higher values of VSI are considered more prone to voltage instability. Therefore, in practice, the buses or areas with VSI values exceeding a certain threshold are identified as potentially restricted or unhealthy. These are the locations where corrective actions may be needed to enhance voltage stability. Important considerations that should be taken into consideration are the following:

- A positive VSI indicates a potentially unstable condition, while a negative value suggests a stable condition.
- Thresholds for identifying unhealthy buses may vary based on the specific characteristics of the distribution network and the desired level of voltage stability [4].

This research work aims to improve the distribution system's power quality by minimizing power losses and improving voltage stability.

### 4.3. Power Flow Analysis

Using the Voltage Stability Index (VSI), the power flow analysis was determined using the Newton-Raphson method. Unhealthy buses and locations in the network are located as follows:

- i. Network data loading
- ii. From the network's collected line and bus data, the bus admittance matrix ( $Y_{bus}$ ) is formed.
- iii. Presuming initial voltages and angles for the bus. The number of iterations was set.
- iv. Using equations (10) and (11), calculate the active and reactive power injected at each bus.
- v. Real power and reactive were introduced as follows:

$$P_i = \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) \quad (10)$$

$$Q_i = -\sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \quad (11)$$

- vi. Evaluation of the mismatched powers and if  $\epsilon \in$ , output load flow solution.
- vii. Computation of element of Jacobian matrix using equation (12).

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (12)$$

where  $J_1 = \frac{\partial P_i}{\partial \delta_k}$ ,  $J_2 = \frac{\partial P_i}{\partial |V_k|}$ ,  $J_3 = \frac{\partial Q_i}{\partial \delta_k}$  and  $J_4 = \frac{\partial Q_i}{\partial |V_k|}$  are the elements of Jacobian matrix.  $\Delta P$  is the active power mismatches and  $\Delta Q$  is the reactive power mismatches. While  $\Delta |V|$  is the magnitude of bus voltages,  $\Delta \delta$  is the phase angle of bus voltages respectively and are called the state variables.

- viii. Verifying that P and Q's scheduled errors are within the stated tolerance. If not, change the variables and iteration count, then return to step 1.
- ix. Assessment of power flows, bus voltage levels, and phase angles.
- x. Updating phase angles and voltages.

Note that the improved CSA was then used to solve the objective function problem. It works faster and guarantees convergence as compared to the GS and GE methods.

## 5. Results

### 5.1. IEEE 33-bus Network With 3-DG Using CSA-SR

Fig. 1 shows the outcomes for the 3-DG scenario with CSA-SR. Three DGs with the ideal locations at buses 23, 27, and 32 have the ideal sizes of  $1.0e06 + j2.2760$ ,  $1.0e06 + j2.6499$ , and  $1.0e06 + j2.7526$ . Using the CSA-SR optimization technique, the average voltage was increased from 0.9488pu to 0.9822pu. The fact that all of the buses fall within the permitted range when comparing the results shows that the scheme outperforms PSO algorithm in controlling system voltage.

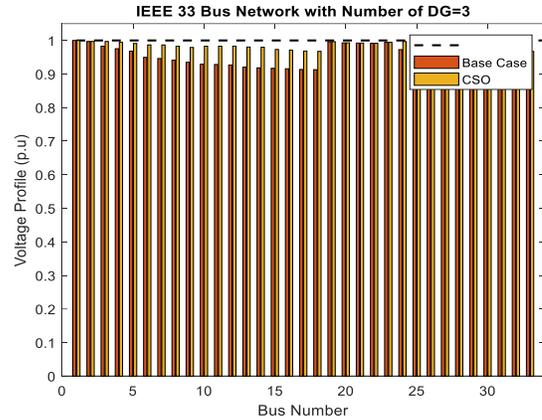


Figure 1. IEEE 33-bus network with 3-DG using CSA-SR.

### 5.2. Comparison of IEEE 33-bus Network Voltage Profile with 3-DG

Fig. 2 presents a comparison of the simulation results from 3-DG for the basic case, PSO, and CSA-SR. The average voltage in the base case was found to be 0.9488pu, but as DGs were applied using the CSA-SR optimization technique, it eventually increased to 0.9669pu and then to 0.9792pu. As a result, the system is discovered to be stable.

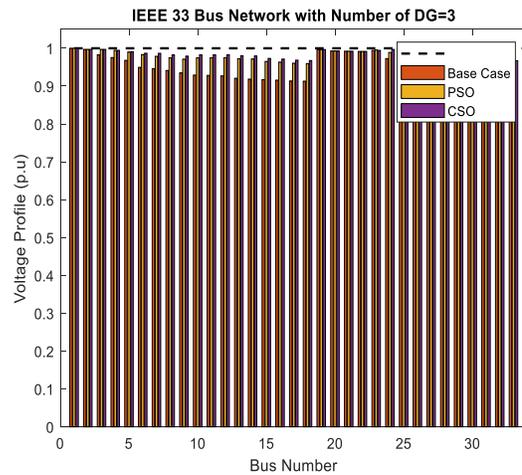


Figure 2. Comparison of voltage profile for IEEE 33-bus network with 3-DG.

### 5.3. Real Power Loss on IEEE 33-bus Network Compared to 3-DG

Fig. 3 illustrates the full system real power loss that was determined from the simulation results to be 202.7071 MW at the base case. As a consequence of DG application employing PSO, which displays a drop of 83.4401 MW, or 41.16%, from the base case result, the actual power loss is discovered to be 119.2670 MW. The installation of three DGs utilizing CSA-SR results in an actual power loss of 113.9630 MW, a reduction of 88.441 MW, or 43.77%, as compared to the base scenario. These demonstrate that the CSA-SR technique performed better than PSO in terms of the device's ideal seating and sizing.

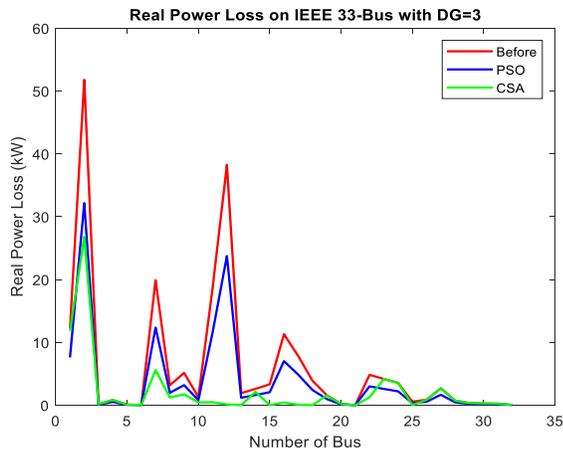


Figure 3. Comparison of real power loss on IEEE 33-bus network with 3-DG.

5.4. Convergence Characteristics of PSO and CSA-SR on the Network with 3-DG

The convergence curves for PSO and CSA-SR on IEEE 33-bus network with 3-DG are shown in Fig. 4; when PSO was applied, it converged after 6 iterations. Also, when CSA-SR was used in the optimal placement of the devices, the convergence is achieved after 5 iterations. Summary of Simulation Results for IEEE 33 Bus is presented in Table 1.

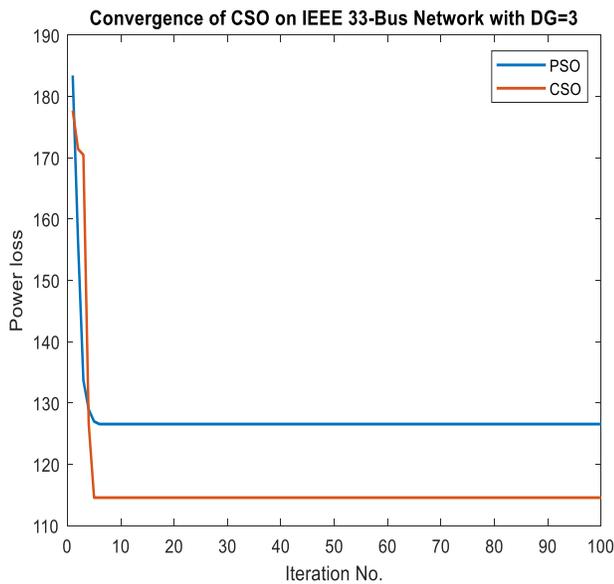


Figure 4. Convergence of PSO and CSA-SR on IEEE 33-bus network with 3-DG.

Table 1. Summary of simulation results for IEEE 33 bus standard network.

Parameter	Base Case (3DG)	PSO	CSA-SR
Average voltage (p.u)	0.9488	0.9699	0.9822
Real power loss (kW)	202.7071	119.2670	113.9630
Convergence rate	Low	High	High

6. Conclusion

This work developed an improved cuckoo search algorithm Based on Success Rate (CSA-SR) for optimal allocation of

Distributed Generation (DG). Voltage Stability Index (VSI) is applied to identify restricted unhealthy buses/areas in the distribution networks. The work is implemented on standard IEEE 33 Bus test systems. Newton Raphson Power Flow (NRPF) technique is used in MATLAB R2019b environment for the power flow analysis. The overall IEEE 33 Bus system real power loss obtained from the simulation result is found to be 202.7071MW at the base case. Following the application of 3 DGs using CSA-SR, the real power loss is found to be 113.9630MW which shows a reduction of 88.441MW which is equivalent to 43.77% as related to base case. The results minimized the system losses while significantly enhancing the voltage profile of the bus voltages as a result of optimal siting and sizing of the DG. These show that CSA-SR technique outperformed PSO.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

- [1] A. Babaita, A. Mati, Y. Jibril, A. Kunya, and I. Abdulwahab, "development of a load frequency control scheme for an autonomous hybrid microgrid," *Zaria Journal of Electrical Engineering Technology*, vol. 11, no. 1, 2022.
- [2] A. S. Abubakar, A. A. Olaniyan, A. Ibrahim, and S. H. Sulaiman, "An Improved Analytical Method For Optimal Sizing And Placement Of Power Electronic Based Distributed Generation Considering Harmonic Limits," in *2019 IEEE PES/IAS PowerAfrica*, pp. 122-127: IEEE, 2019.
- [3] G. Olarinoye and I. Abdulwahab, "Comparative Analysis and Simulation of the dq Reference Frame Model of the Three Phase Induction Motor and its Modification," *Arid Zone Journal of Engineering, Technology and Environment*, vol. 18, no. 1, pp. 41-52, 2022.
- [4] M. U. Iliyasu, M. Ozohu, S. S. Yusuf, I. Abdulwahab, A. Ehime, and A. Umar, "Development of an Optimal Coordination Scheme For Dual Relay Setting In Distribution Network Using Smell Agent Optimization Algorithm," *Covenant Journal Of Engineering Technology*, 2022.
- [5] I. Abdulwahab, A. S. Abubakar, A. Olaniyan, B. O. Sadiq, and S. A. Faskari, "Control of Dual Stator Induction Generator Based Wind Energy Conversion System," in *2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development (NIGERCON)*, 2022, pp. 1-5: IEEE.
- [6] B. Singh and S. S. J. p. Rawat, "Optimal placement of DG with battery energy storage in distribution network for power loss minimization using combined dispatch & combined PLS strategy," vol. 7, p. 8, 2020.
- [7] R. Kurniawan *et al.*, "The effect of distributed generator injection with different numbers of units on power quality in the Electric Power System," vol. 1, no. 2, pp. 71-78, 2021.
- [8] S. Kawambwa, N. Hamisi, P. Mafale, and H. J. E. I. Kundacli, "A cloud model based symbiotic organism search algorithm for DG allocation in radial distribution network," pp. 1-18, 2022.
- [9] A. Selim, S. Kamel, A. A. Mohamed, and E. E. J. S. Elattar, "Optimal allocation of multiple types of distributed generations in radial distribution systems using a hybrid technique," *Sustainability*, vol. 13, no. 12, p. 6644, 2021.
- [10] A. Bawa, M. Uthman, F. E. Shaibu, K. S. J. E. J. o. E. Oyewale, and T. Research, "Optimal Sizing and Sitting of Distributed Generation for Power Quality Improvement of Distribution Network," *European Journal of Engineering and Technology Research*, vol. 4, no. 10, pp. 18-23, 2019.
- [11] A. Azhar and A. Ahmad, "Optimal Reconfiguration of Power Distribution Network Using Hybrid Firefly and Particle Swarm Optimization Algorithm", *PakJET*, vol. 4, no. 4, pp. 23-28, Dec. 2021.