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Mitigating Phase Imbalance in Distribution Networks with Optimal DSTATCOM Placement using Hybrid Bacteria Foraging and Cuckoo Search Algorithm.

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Abstract- This research presents the optimal placement and sizing of a Distribution Static Compensator (DSTATCOM) on the 11 kV Malali feeder for phase balancing, power loss reduction, and voltage profile improvement. The study addresses challenges of voltage imbalance and excessive power losses common in unbalanced radial distribution networks. A hybrid optimization approach combining the Bacterial Foraging Optimization (BFO) and Cuckoo Search Optimization (CSO) algorithms was developed to determine the location and reactive power injection of the DSTATCOM. The 11 kV Malali feeder, modeled in MATLAB R2023b using the forward–backward sweep load flow method, served as the test network. Simulation results showed that Bus 15 was the most effective location for DSTATCOM placement. The hybrid BFO–CSO algorithm achieved a 75.7% reduction in real power loss, a 90.7% reduction in reactive power loss, and a 10.2% improvement in voltage profile, raising the minimum bus voltage from 0.889 p.u. to 0.98 p.u. The results demonstrate that the proposed hybrid optimization technique provides superior performance compared to standalone algorithms, achieving improved voltage stability, minimized losses, and enhanced phase balance in distribution networks. The study concludes that the hybrid BFO–CSO approach is an effective tool for multi-objective optimization in power distribution systems.

Keywords: Hybridization, Cuckoo search, Bacterial foraging, Voltage imbalance

I. INTRODUCTION

The reliability and efficiency of electric power distribution systems are critical to ensuring stable electricity supply, minimizing technical losses, and maintaining acceptable power quality standards. Among the various challenges facing distribution networks, phase imbalance remains a persistent and significant problem, particularly in developing countries where infrastructural limitations and non-uniform load distributions are common[1 2]. Phase imbalance, often caused by uneven allocation of single-phase loads, faulty connections, or unplanned expansions, results in unequal currents across the three phases of the distribution network, leading to adverse effects such as voltage fluctuations, increased power losses, excessive heating of transformers, and reduced equipment lifespan [3].

In Nigeria, the problem is particularly evident in residential and semi-urban distribution feeders. The widespread use of single-phase connections and the absence of robust load management practices have worsened voltage imbalance issues, leading to customer complaints, frequent equipment failures, and reduced operational efficiency[4]. Conventional reactive power compensation techniques, such as capacitor banks, often fall short in addressing the dynamic and phase-specific nature of these imbalances.

One promising solution is the use of Distribution Static Compensators (DSTATCOMs), which are power-electronic-based devices connected in shunt with the distribution line. Unlike traditional compensation devices, DSTATCOMs are capable of dynamically injecting or absorbing reactive power on a per-phase basis, thereby correcting voltage unbalance and improving overall power quality [5]. Several studies have demonstrated the effectiveness of DSTATCOMs in voltage regulation, power factor correction, and harmonic mitigation in distribution networks [6 7]. However, the performance of DSTATCOM systems is highly sensitive to their placement and sizing within the network. Improperly placed compensators may lead to suboptimal performance or even worsen network conditions. A set of three phasors, such as three-phase voltages or currents, is balanced if all phasors have the same magnitude and are phase-shifted symmetrically by 120◦ to each other. Any deviation of the magnitudes and/or phase-shifts from these conditions causes the considered set of phasors to be unbalanced. According to an alternative definition, a set of three phase voltages or currents is balanced if it decomposes only into positive-sequence voltages or positive-sequence currents, respectively; otherwise, it is unbalanced [3]. Distribution networks are inherently unbalanced; the magnitudes of the currents carried by each phase are not the same. The sum of these phase currents is not equal to zero and flow through the neutral conductor. Some of the reasons for this are as follow [8] Any large single-phase load, or a number of small loads connected to only one phase cause more current to flow from that particular phase causing voltage drop on line, Switching of three phase heavy loads results in current and voltage surges which cause unbalance in the system, Unequal impedances in the power transmission or distribution system cause differentiating current in three phases, With continuous operation of motor in various environment cause degradation of rotor and stator windings. This degradation is usually different in different phases, affecting both the magnitude affecting both the magnitude and phase angle of current waveform

II. LITERATURE REVIEW

These techniques include load balancing, phase shifting, reconditioning of distribution lines, bifurcation of distribution lines, distribution energy storage, and reconfiguration of distribution lines, application of capacitor banks and the use of FACTs devices using both heuristic, stochastic and computational methods [9]. For example, reference [10] employed simulated annealing to address phase balancing by optimizing the non-linear objective function to determine the optimal number of phase moves and line flows. In [11], a genetic algorithm to optimize the phase configuration of distribution transformers and laterals connected to the primary feeder by considering the phase loading of transformers was introduced. Reference [12] proposed a heuristic algorithm for rephasing single and double-phase laterals to enhance balance at various points by evaluating power loss and phase current magnitudes, especially accommodating time-varying loads. Research conducted by [13] investigate use of zig-zag transformers to mitigate harmonic distortion in three-phase four-wire distribution networks under varying power conditions. While [14] proposed a novel method for optimizing consumer allocation across phases in LV distribution networks by utilizing network topology data and energy consumption records, the method effectively minimizes phase current disparities. In [15], a combined network reconfiguration and phase balancing approach in low and medium voltage distribution feeders was proposed, utilizing neural networks and heuristic methods to maintain balanced phases by selectively activating reconfiguration switches and adjusting consumer phase connections. Reference [16] devised a rephasing strategy for laterals and distribution transformers to improve three-phase balancing using an immune algorithm, formulating a multi-objective function considering phase current imbalance, customer service interruption costs, and labour costs. While [17] developed a knowledge-based expert system to determine rephasing strategies for distribution feeders to enhance three-phase balance by reducing neutral current magnitudes. In [18], a hybrid solution involving a zig-zag transformer and a three-phase, three-leg DSTATCOM for reactive power compensation, harmonics current mitigation, neutral current compensation, load balancing, and voltage regulation at the point of common coupling was implemented. Reference [19] employed a combined approach using genetic algorithms and the OpenDSS power flow solver to optimize phase reconfiguration and capacitor placement. While [20] proposed method to address three-phase voltage imbalance in distribution networks by utilizing photovoltaic and energy storage systems by accessing the transformer's neutral point and employing a PWM active inverter to generates a reverse voltage to counteract the imbalance.

III. METHODOLOGY

This section presents the methodology deployed to optimize the placement of Distribution Static Compensator (DSTATCOM) in the 11kV Malali distribution feeder. The aim is to enhance phase balancing, reduce power losses, and improve the voltage profile. The methodology incorporates simulations using forward-backward sweep load flow method, and optimization is carried out using the hybrid Bacterial Foraging Optimization (BFO) and Cuckoo Search Optimization (CSO) algorithm. Key components such as, the hybrid algorithm, data collection, performance metrics, and the simulation process are discussed herein.

(A) Siting and Sizing of D-STATCOM

The siting of D-STATCOM is done by carrying out unbalance load flow analysis and determining the bus with the largest phase imbalance while the sizing was done using Bacterial Foraging Optimization (BFO) and Cuckoo Search Optimization (CSO) algorithm,

(B) Objective Function and Constarints

The objective function for the optimization is to minimize the differences in magnitude of phase voltages as shown in equations (1) while equation (2) and (3) are the constraints on bus voltages and line currents

$$F(x) = \min[\mathrm{abs}(V_a - V_b) + \mathrm{abs}(V_a - V_c) + \mathrm{abs}(V_b - V_c)] \quad (1)$$

using the following constraints:
The magnitude of the voltage

$$V_{min} \le |V_i| \le V_{max} \quad \forall_i \in N_b \quad (2)$$

The current limit of branches

$$|I_i| \le I_{imax} \quad (3)$$

(C) Hybridization of Cuckoo Search and Bacteria Foraging Algorithm

The development of the BFO-CSA technique was motivated by the need to combine the benefits of cuckoo search algorithms with bacteria foraging algorithm. The primary concept behind BFO-CSA is to combine CSA social thinking capacity with BFA local search capabilities. Because CSA and BFA are both population-based algorithms, the hybrid BFO-CSA technique is likewise population-based and hence finds the global answer. The algorithmic flowchart is shown in Figure 1

Table 1: Cuckoo Search Parameters

Sr. No.	Parameter	Values
1	Npar	100
2	Varlo	-5
3	Number of Population	20
4	varHi	5
5	nC	5
6	maxCycle	100
7	Min Egg	2
8	Max Egg	4
9	N0. Clusters	1
10	Lambda var	9
11	Control of Egg	5

Table 2: Bacteria Foraging Parameters

No.	Parameter	Values
1	Dimension	2
2	Number of Bacteria	20
3	Maximum number of steps, N	10
4	Maximum Number of chemotactic steps	20
5	Number of Chemotactic Steps, Nc	10
6	Number of reproduction Steps Nre	20
7	Number of Elimination Dispersal Steps Ned	100
8	Probability, Ped	0.9
9	Size of Step, C(i)	0.01

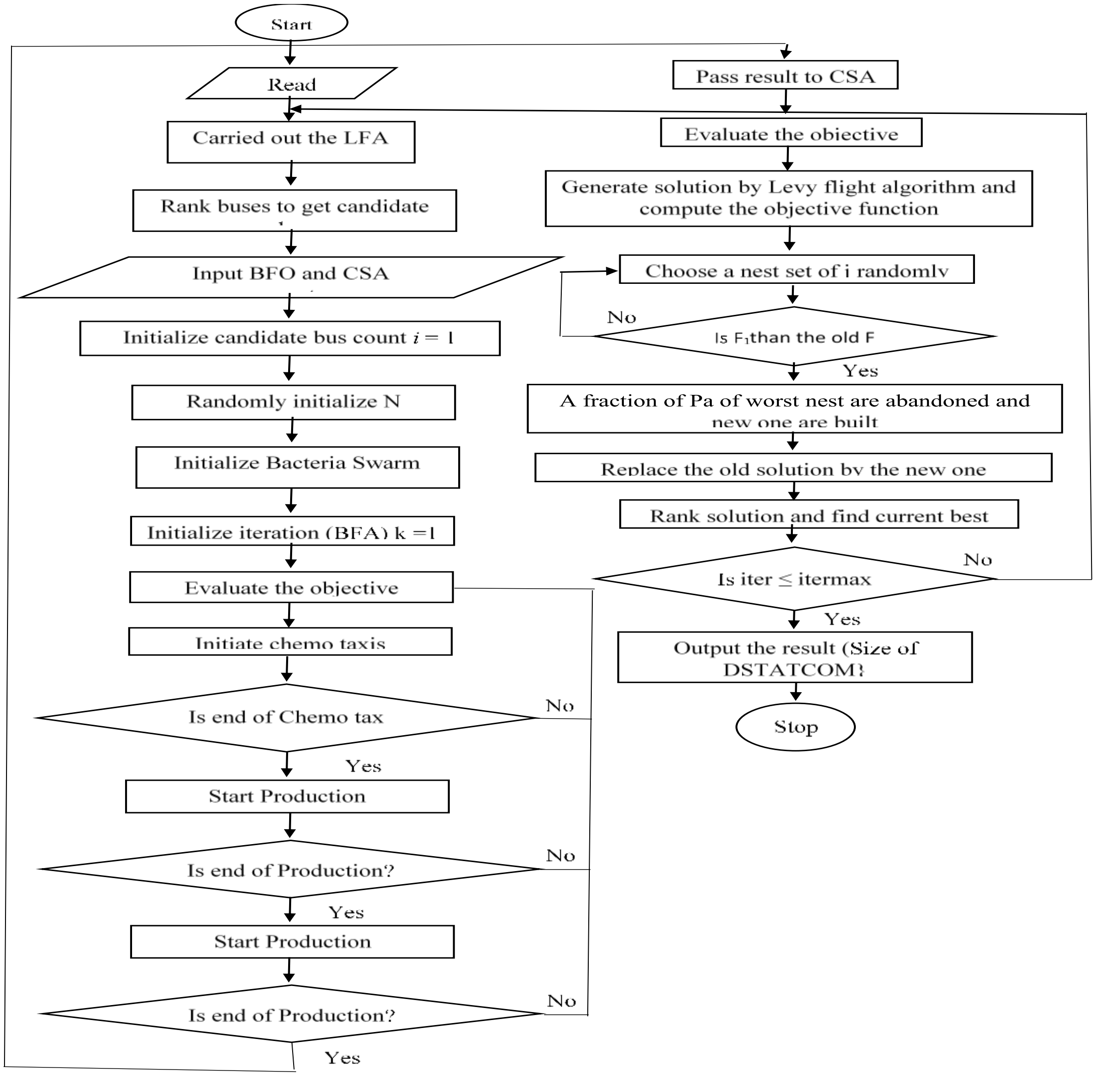

Figure 1: Flowchart of hybrid BFO-CSA

IV. DESCRIPTION OF THE TEST NETWORK

The 11kV Malali feeder, located within the Kaduna Electric distribution network, is selected as the case study for this research the one line diagram is shown in Figure 2. This feeder supplies a mix of residential, commercial, and industrial loads, leading to unbalanced load conditions, voltage fluctuations, and significant power losses

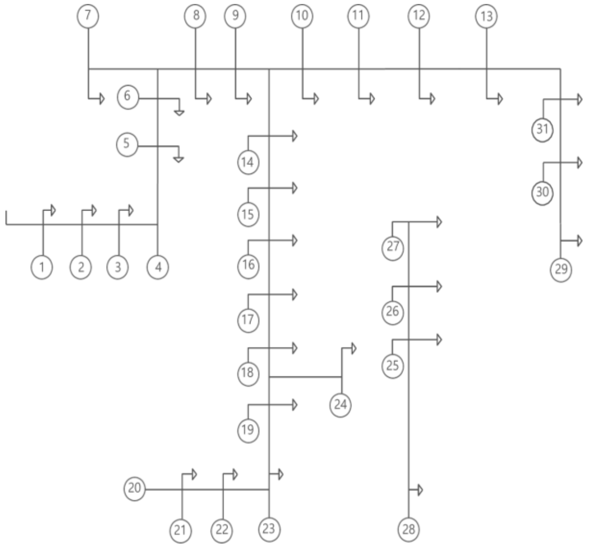

Fig: 2: Single line diagram of 11kV Malali feeder

V. RESULTS AND DISCUSSION

Results of Voltage Profile with and without DSTATCOM

For each bus combined sensitivity factor (CSF) are analyzed and the buses with high CSF are taken as a candidate bus for placement. Hence, those weak buses are considered for optimal placement of D-STATCOM after BFO-CSA optimization. Three phase voltage profile without DSTATCOM is as shown in Figure 3

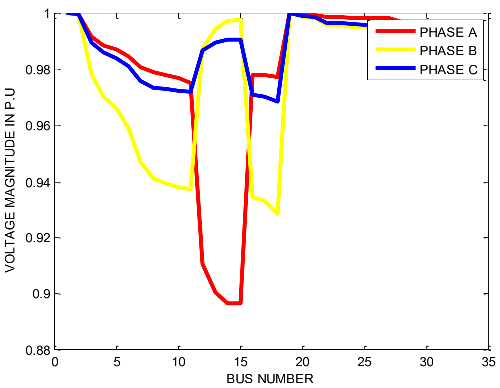

Figure 3: Three phase voltage profile without DSTATCOM

Figure 3 is the graph of the three-phase voltage without DSTATCOM, phase A voltage went as low as 0.88 volt per unit at bus 15, this is the minimum of all the voltages at the same bus phase B voltage is 1 per unit while phase C voltage is 0.985 per unit. This bus is the bus with highest level of 3 phase voltage imbalance; thus, this suggests the appropriate location for siting the DSTATCOM

Figure 4 shows the three-phase voltage profile with the application of DSTATCOM.

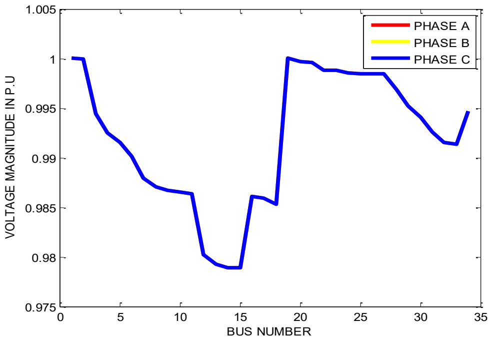

Figure 4: Three Phase Voltage profile with DSTATCOM

it can be seen from the graph that the imbalanced in voltage has been almost totally eliminated and the negligible values of imbalance in voltage is shown in Figures 5 and 6

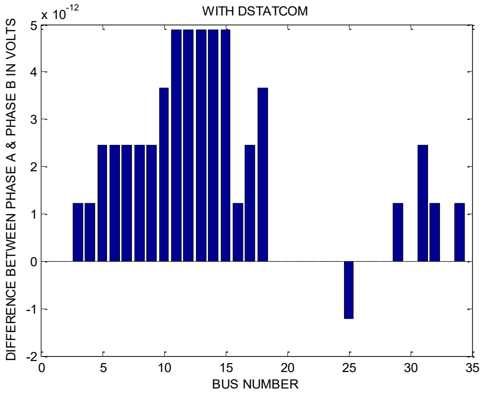

Figure 5: Difference in voltage between Phase A and Phase B

Figure 5 is the difference in voltage between Phase A and Phase B, the maximum difference recorded is $5x10^{-12}$ this is totally insignificant this demonstrates the ability of DSTATCOM to correct imbalance in voltage on a distribution network

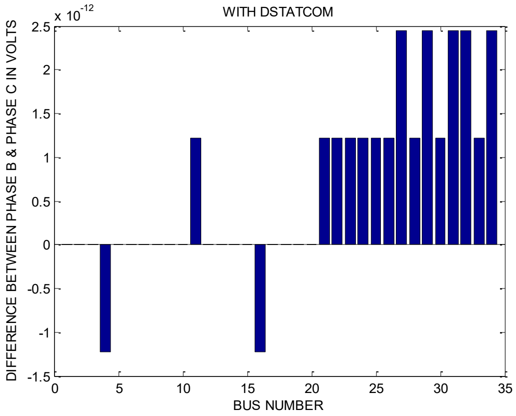

Figure 6: Difference in voltage between Phase A and Phase C

Figure 6 is the difference in voltage between Phase A and Phase C, the maximum difference recorded is $2.5x10^{-12}$ this is totally insignificant this demonstrates the ability of DSTATCOM to correct imbalance in voltage on a distribution network across the whole length of the distribution line.

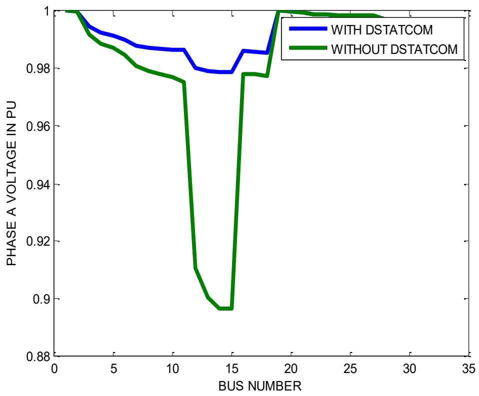

Figure 7: Voltage profile with and without DSTATCOM for Phase A

Fig 7 is the voltage profile with and without DSTATCOM for Phase A, it is seen that the voltage without DSTATCOM went as low as 0.899 p.u at bus 15 (FRCN quarters), this is the bus with the highest voltage disparity however the voltage rose to 0.985 with the placement of DSTATCOM

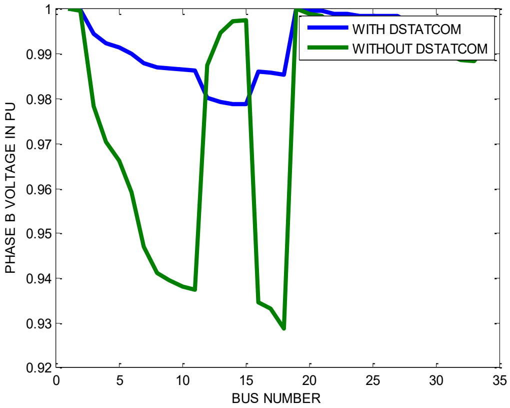

Figure 8: Voltage profile with and without DSTATCOM for Phase B

Fig 8 is the voltage profile with and without DSTATCOM for Phase B, it is seen that the voltage without DSTATCOM went as low as 0.928 p.u at bus 18, this is the bus with the highest voltage disparity however the voltage rose to 1 p.u with the placement of DSTATCOM, this is a clear demonstration of the ability of DSTATCOM to improve voltage profile across the whole length of the line

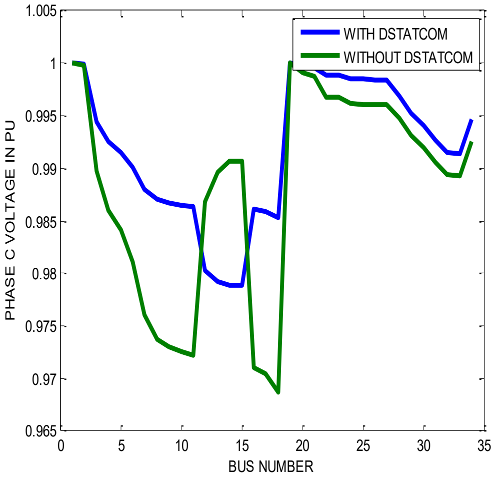

Figure 9: Voltage profile with and without DSTATCOM for Phase C

Fig 9 is the voltage profile with and without DSTATCOM for Phase C, it is seen that the voltage without DSTATCOM went as low as 0.928 p.u at bus 18, this is the bus with the highest voltage disparity however the voltage rose to 1 p.u with the placement of DSTATCOM, this is a clear demonstration of the ability of DSTATCOM to improve voltage profile across the whole length of the line

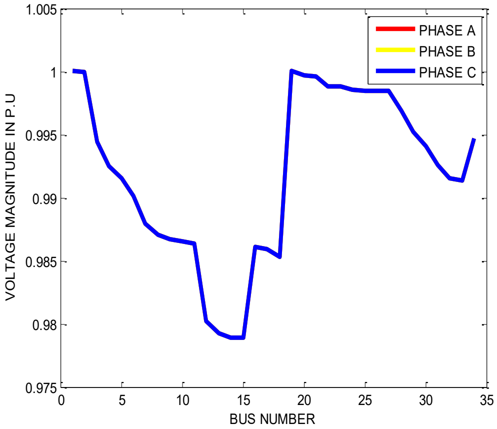

Figure 10: Voltage profile with and without DSTATCOM for Phase C

Fig 10 is the voltage profile with and without DSTATCOM for the three phase voltages it is seen that the minimum voltage recorded was 0.98 p.u at bus 15, furthermore it can be seen that no disparity between the three phase voltages with the placement of DSTATCOM, this is a clear demonstration of the ability of DSTATCOM to correct imbalance in voltage across the whole length of the line.

Figure 10 is the graph of hybrid CSA and BFO convergence curve, the graph determines the amount of reactive power injection per phase that will balance the three-phase voltage and not violate the voltage and power constraints.

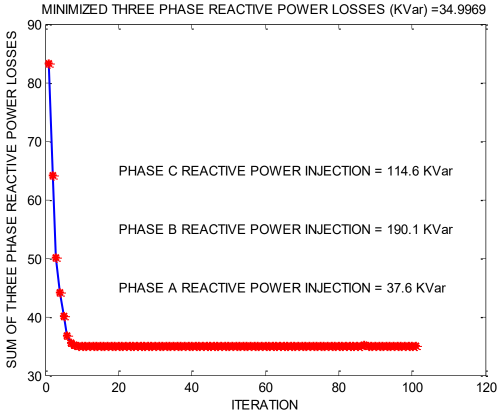

Figure 10: Convergence Graph of Hybrid CSA and BFA Algorithm Process

The respective optimal values of injected reactive power for phase A, B and C are 37.6KVar, 190.1 KVar and 114.6 KVar, the total three reactive power losses with these injected values is 34.9969 KVar, without DSTATCOM the losses was 375.8kVar, which represent 90.7 % reduction in the reactive power loss. Also, all the phases certified the voltage constraint range between 0.95 pu to 1.05 pu. The voltage at bus 15 was improved from 0.899 pu to 0.98 pu representing 9 % improvement when compared to the base case.

VI. CONCLUSION

In conclusion, this research work presented the formulation and implementation of a hybridized BFO-CSA algorithm to help in reducing Malali distribution network power losses and improving voltage profile by optimal location and sizing of D-STATCOM. To achieve this end relevant literatures were reviewed that served as theoretical foundation for the research work. Simulations were carried out using the method of unbalanced load flow to determine the bus with the highest degree of voltage imbalance that will be selected for D-STATCOM allocation. Bus 15 is the most effective bus for placing D-STATCOM in terms of power loss reduction and voltage profile improvement. The base case MATLAB simulation results indicate that the Malali feeder encountered a total reactive power loss of 375.8kVar. Moreover, 15 of the buses were not under the acceptable voltage range. After D-STATCOM integration at bus 15, 90.7% reactive power loss reduction is obtained and all bus voltages are kept under the acceptable range. The BFO-CSA method also improved the lowest bus voltage from a value of 0.899pu to 0.98pu. Furthermore, simulation has also performed to investigate the effectiveness of the hybrid BFO-CSA method. The comparison result obtained indicated that BFO-CSA mechanism gives a better result than both CSA and BFA in terms of power loss reduction and size of D-STATCOM.

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