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Optimal Dynamic Stability Enhancement of the Government Feeder Lafia in The Abuja Distribution Company Using Dstatcom

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ABSTRACT: *The location and sizing of DSTATCOM is an important factor for optimal operation of radial distribution system. This research employs Artificial Bee Colony to determine the optimal location and sizing of a Distribution STATCOM to minimize total line loss and to improve voltage quality within the permissible range. ABC was tested on the IEEE 33Bus and then also applied to the Govt-House 15 Bus system in Lafia, Nasarawa State, Nigeria. The performance of the ABC was compared with and without DSTATCOM installed. Modelling of the RDS and simulation was done in MATLAB environment and the results for IEEE 33 Bus. The real power loss was reduced by 26.6% from 201.77kw to 148.05 kW while the reactive power loss was reduced by 26.7% from 134.99kvar to 98.93 kvar. The number of Bus voltage violation reduced from 21 to 13. For the Government House feeder, the real power loss was reduced by 63.9% from 171.65kw to 61.87kw. While the reactive power loss was reduced by 64.01% from 195.47 kvar to 70.35 kvar. The number of Bus voltage violation reduced from 12 to 1. The findings from the research shows that that ABC has performed better than other result in literature. The voltage profile, active power loss, computational time was improved with the DSTATCOM. Therefore, ABC made improvement on the standard IEEE 33-bus RDS and the Govt-House 15-Bus RDS with improvements in the voltage profile and reduction in active power loss and reactive power loss.*

KEYWORDS: optimal dynamic stability, enhancement, government feeder Lafia, Abuja distribution company, Dstatcom

INTRODUCTION

The technological advances in power semiconductors permit the development of devices that react more like an ideal switch, totally controllable, admitting high frequencies of commutation to major levels of tension and power (Peter, 2017). The concept of flexible AC transmission system (FACTS) devices were associated with the development of the renewable energy sources such as fuel cells, wind energy and solar cells, another factor to keep in mind in the development and configuration of the electrical system. FACTS devices require electronic equipment based on power converters that facilitate the integration of these sources of energy, without damaging over the reception quality of the users connected to the electricity network (Patel and Umar, 2018). The FACTS controllers offer great opportunities to regulate the transmission of alternating current (AC), increasing or decreasing the power flow in specific lines and responding almost instantaneously to the stability problems. The potential of this technology is based on the possibility of controlling the route of the power flow and the ability of connecting networks that are not adequately interconnected, giving the possibility of trading energy between agents (Tambey and Kothari, 2015). There are many types of FACTS devices depending on the way are connected in the network such as; series, shunt and the combination of the two. There are many types of FACTS devices depending on the way they are connected in the network such as; series, shunt and the combination of the two. Examples of FACTS devices include; static compensator (STATCOM), Thyristor control series compensator (TCSC), series capacitor synchronous compensator (SCSC), Unified power flow controller (UPFC), generalized unified power flow controller (GUPFC) etc. UPFC is perhaps the most versatile of the FACTS controllers, offering a unique combination of shunt and series compensation which guarantee flexible power system control (Sharma and Vadhera, 2016). The three steady state models of UPFC according to (Elkholy, 2014) are; decoupled injection and comprehensive newton raphson (NR) models. The flexible power flow control and high dynamics can be successfully achieved by applying electronic power converters. It is particularly beneficial to use power converters based on full controlled switches, such as Gate Turn Off thyristors (GTO) and the more recently available high-power Insulated Gate Bipolar Transistor (IGBT), which are suitable to handle higher switching frequencies (Gupta *et al.*, 2015). The work investigates the dynamic stability enhancement of the Government feeder, Lafia in the Abuja distribution company using DSTATCOM.

LITERATURE REVIEW

Review of Fundamental Concepts

DSTATCOM is a member of FACTS devices consists of two solid state synchronous voltage source converters coupled through a common DC link. The DC link provides a path to exchange active power between converters. The series converter injects a voltage in series with the system voltage through a series of transformer. The power flow through the line can be regulated by controlling voltage magnitude and the angle of series injected voltage (Kalyani, and Tulasiram, 2010). The injected voltage and line current determine the active and reactive power injected by the series converter. The converter has a capability of electrically generating or absorbing the reactive power. The shunt converter has a capability of independently supplying or absorbing reactive power to regulate the voltage of the AC system (Patel and Umar, 2018). The DSTATCOM is a device placed between two buses referred to the DSTATCOM sending bus (B1) and the DSTATCOM receiving bus (B2), It consists of two voltage-sourced converters (VSCs) with a common DC-link. For the fundamental frequency model, the VSCs are replaced by two controlled voltage sources (Gomez, 2011).

By applying the pulse width modulation (PWM) technique to the two VSCs, the following equations for magnitudes of shunt and series injected voltages can be obtained. Both voltage sources are modeled to inject voltages of fundamental power system frequency only. The DSTATCOM is placed on high-voltage distribution network; the arrangement requires step-down transformers to allow the use of power electronic devices for the DSTATCOM. The series converter injects an AC voltage (Mohammad and Ewald, 2015).

The shunt converter injects controllable shunt voltage such that the real component of the currents in the shunt branch balances the real power demanded by the series converter. The reactive power cannot flow through the DC-link. It is absorbed or generated locally by each converter. The shunt converter operated to exchange the reactive power with the AC system provides the possibility of independent shunt compensation for the line (Hingorani and Gyugyi, 1999). If the shunt injected voltage is regulated to produce a shunt reactive current component that will keep the sending bus voltage at its pre-specified value. In order to show how the line power flow can be affected by the DSTATCOM, it is placed at the beginning of the distribution.

Flexible Alternating Current Transmission Systems (FACTS) devices have been widely used in power systems around the globe. These devices are used to enhance the controllability and maximize the power transfer capability of the electrical network (Hingorani and Gyugyi, 1999). The semi-conductor devices such as diodes, transistors, thyristors and gate turn-off thyristors (GTO) are applied to develop the various types of FACTS. The FACTS devices have the ability to control many parameters of transmission systems such as; the series impedance, the shunt impedance, the currents, the voltage magnitude, and the phase angle. FACTS controllers are power electronics-based system and other static equipment that have the capability of controlling various electrical parameters in transmission networks which can be adjusted to provide adaptability conditions of transmission network. FACTS controllers have been proved that they can be used to enhance system controllability resulting in total transfer capability (TTC) enhancement and decreasing power losses in transmission networks (Patel and Umar, 2018). The optimal performance of using FACTS controllers to increase TTC and minimize losses should be obtained by choosing the maximum numbers, parameter settings, and locations in transmission systems. Modern heuristics optimization techniques are successfully implemented to solve complicated optimization problems efficiently and effectively (Patel and Umar, 2018).

DSTATCOM are the most versatile and complex power electronic equipment applied to control and for the power flow optimization in electrical power transmission systems. It offers major potential advantages for the static and dynamic operation of transmission lines. The DSTATCOM combines the functions of several FACTS devices and is capable of implementing voltage regulation, series compensation, and phase angle regulation at the same time. Thus, realizing the separate control of the active power and reactive power

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transmitted simultaneously over the line. The DSTATCOM thus provides effective means for controlling the power flow and improving the transient stability in a power network. According to (Patel and Umar, 2018), DSTATCOM is the most effective Flexible Alternating Current Distribution System (FACTS) device which is able to optimize the power transfer capability of interconnected power systems (Udhaya, 2012). The DSTATCOM can be used to control the line power flow and voltage bus individually or simultaneously. Now, the implantation of FACTS devices in load flow algorithms is considered as a fundamental requirement in planning, operation, and the control. Generally, the existing load flow programs need to be modified to incorporate these devices. The required modifications due to many reasons such as; addition reference buses related to the number of FACTS have to be added in the network, the impedances of FACTS have to be incorporated into original admittance matrix, and the powers contributed by FACTS have to be included into power mismatches vector. Some of excellent research works have been done to reduce the complexity of load flow programs with the DSTATCOM device (Chansareewittaya and Jirapong, 2012). The DSTATCOM is the most powerful and versatile FACTS equipment used to control the power flow and stability of the power system. The DSTATCOM uses solid state devices, which provide functional flexibility, generally not attainable by conventional thyristor-controlled systems (Patel and Umar, 2018). The DSTATCOM is a combination of a static compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link. The DC terminal of the two converters is connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line (Patel and Umar, 2018). Hence, the series converter will exchange active and reactive power with the line. DSTATCOM can be act static as well as dynamic condition also. Static is an analysis at the steady state condition and dynamic is an analysis at the transient condition such as faults occurs in transmission system. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle (Patel and Umar, 2018).

According to IEEE definition and standard DSTATCOM is combination of both static compensator (STATCOM) and static synchronous series compensator (SSSC). Those devices are coupled via common dc power link to allow bidirectional flow of real power between the series output terminal of SSSC and the shunt output terminal of STATCOM.

Computation of load current

Considering the k^{th} bus of a distribution power network, the load current at bus k is expressed as (Jain *et al.*, 2014):

$$I_{L(k)} = \frac{P_k - jQ_k}{V_k^*} \qquad (2.1)$$

for $k = 1, 2, 3, ..., N_{Bus}$

Where, N_{Bus} is the total number of buses,

P_k and Q_k are the real and reactive power demand at bus k respectively,

V_k^* is the voltage conjugate at bus k

BIBC matrix formation

The relationship between load currents (I_L) and branch currents (I_B) can be established by applying the Kirchhoff's current law (KCL) to the distribution network. The network branch currents are expressed as (Jain *et al.*, 2014):

$$I_{B1} = I_{L2} + I_{L3} + I_{L4} + I_{L5} + I_{L6} \tag{2.2}$$

$$I_{B2} = I_{L3} + I_{L4} + I_{L5} + I_{L6} \tag{2.3}$$

$$I_{B3} = I_{L4} + I_{L5} + I_{L6} \tag{2.4}$$

$$I_{B4} = I_{L5} \tag{2.5}$$

$$I_{B5} = I_{L6} \tag{2.6}$$

Equations (2.2) to (2.6) can be expressed in a matrix form as follows (Jain *et al.*, 2014):

$$\begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{L2} \\ I_{L3} \\ I_{L4} \\ I_{L5} \\ I_{L6} \end{bmatrix} \tag{2.7}$$

The above matrix can be written in a more compact form as (Jain *et al.*, 2014):

$$[I_B] = [BIBC][I_L] \tag{2.8}$$

$BIBC$ is the Bus Injection to Branch Current matrix and contains values of 0 and 1.

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Forward sweep

Since voltage values of source buses are known, the receiving end bus voltages can be determined by deducting the corresponding branch voltage drop from values of the sending end voltages. The voltage at bus k is given by (Jain *et al.*, 2014):

$$V_k = V_i - I_{B(ik)} * Z_{ik} \tag{2.9}$$

$for\ ik = 1, 2, 3, ..., N_{Branch}$

Where, N_{Branch} is the total number of branches,

V_k and V_i are the receiving and sending end voltages of branch ik respectively,

$I_{B(ik)}$ is the current flowing in branch ik ,

Z_{ik} is the impedance of branch ik .

2.1.4 Power losses

The active and reactive power losses of branch ik are calculated using (Jain *et al.*, 2014):

$$P_{ik(loss)} = \left| I_{B(ik)} \right|^2 * \Re\left(Z_{ik}\right) \tag{2.10}$$

$$Q_{ik(loss)} = \left| I_{B(ik)} \right|^2 * \Im\left(Z_{ik}\right) \tag{2.11}$$

Total active and reactive power losses of a radial distribution system can be determined by taking the summation of individual active and reactive power losses using equations (2.10) and (2.11) respectively.

FACTS AND FACTS CONTROLLERS

FACTS stands for Flexible AC Transmission System and refers to alternating current transmission systems that incorporate power electronic-based and static controllers. These systems aim to enhance controllability and increase power transfer capability. FACTS controllers are power electronic-based systems and static equipment that provide control over one or more parameters of AC transmission systems, as defined by the IEEE PES Task Force.

Classification of FACTS controllers

FACTS (Flexible AC Transmission System) controllers are categorized into two types: thyristor-controlled controllers, including Thyristor Controlled Reactor (TCR), Thyristor Controlled Series Compensator (TCSC), and Static Var Compensator (SVC); and voltage source inverter-based controllers, including Static Synchronous Series Compensator (SSSC), Distribution Static Compensator (D-STATCOM), and Unified Power Flow Controller (UPFC). These controllers play a crucial role in enhancing the flexibility and efficiency of power transmission systems.

Categories of FACTS controllers

Generally, FACTS controllers are categorised based on the nature of their connection in electric power systems. The four basic categories of FACTS controllers are as follows (Singh *et al.*, 2012): i) Series connected; ii) Shunt connected; iii) Combined series-series connected; and iv) Combined series-shunt connected.

Optimal siting and sizing techniques

Researchers have developed and applied several techniques for optimal siting and sizing of FACTS Controllers in electric power networks in order to enhance the network performance by reducing power loss and improving voltage profile. Some of the techniques are as follows

Analytical Techniques

This approach is on the basis of simplified network assumptions. The techniques are employed for various sensitivity analysis for improving the dynamic stability in power networks. Some of the analytical techniques used for optimal siting and sizing of FACTS Controllers in power networks include (Singh *et al.*, 2015): Eigen Value Analysis (EVA), Modal Analysis (M.A), Residual Based Method (RBM), Index Method (IM), Sensitivity Based Method (SBM), etc.

OPTIMAL ALLOCATION OF DSTATCOM

DSTATCOM

The DSTATCOM is used in distribution systems for load flow analysis. This paper proposes a load flow algorithm for radial distribution systems, incorporating backward and decomposed forward sweeps. The optimal location and size of the DSTATCOM are determined through an optimization process considering technical and economic feasibility. Various optimization-based techniques have been suggested for solving the placement and sizing problems of DSTATCOMs, categorized into analytical methods, artificial neural network-based methods, metaheuristic methods, sensitivity approaches, and hybrid approaches. The objective is to enhance power quality and minimize total cost in radial distribution systems.

Analytical methods

Analytical methods, techniques, and tools are widely used to analyze and interpret data in various fields. In the context of optimizing the allocation of D-STATCOM, a method was proposed to identify optimal solutions by considering mathematical and statistical models. Approximations were used to reduce computational complexity. Hussain & Subbaramiah (2013) developed an analytical method for determining the optimal position of D-STATCOM in a distribution network, considering power losses and voltage profile. Their method was compared to the genetic algorithm (GA). Amin et al. (2018) proposed an analytical technique for optimal placement and sizing of DG and D-STATCOM in radial distribution systems. Power loss minimization and voltage profile improvement were the main objectives. The algorithm was validated using standard IEEE test systems and compared with other techniques.

Artificial Neural Network based methods

Artificial Neural Networks (ANN) have been used to model nonlinear systems and find optimal placements of DSTATCOM in distribution networks under faults. However, ANN is not suitable for optimal D-STATCOM sizing. ANN has also been utilized to allocate DVR and D-STATCOM in distribution networks to mitigate voltage sag during faults. The best placement for D-STATCOM is determined based on the greatest deviation of voltage from the target value. Different optimization techniques, such as SFLA and PSO, have been used to train ANN for estimating STATCOM voltages and reactive powers, outperforming other methods in terms of efficiency.

Metaheuristic methods

Metaheuristics, such as immune algorithm (IA), particle swarm optimization (PSO), genetic algorithm (GA), and cuckoo search algorithm (CSA), have been widely used to solve D-STATCOM allocation problems in distribution networks. These algorithms are effective in handling complex environments with multiple objectives and constraints. Researchers have applied these algorithms to optimize the location, sizing, and settings of D-STATCOM to improve power quality, reduce energy loss, cost, and voltage profile issues. Different objective functions and optimization constraints have been considered, including installation cost, energy loss, power congestion, line losses, voltage dips, and load carrying capacity. The results of these studies demonstrate the effectiveness of metaheuristic algorithms in achieving optimal D-STATCOM placement and sizing, leading to improved system performance and reduced power losses.

MATERIALS AND METHODS

The materials used in the design of this research work were highlighted in the following sub heading:

Materials

The materials that were used for the work include:

Computer system

The personal computer was the hardware material used for carrying out the thesis. All simulations analyses were carried out using HP Notebook PC with the following specifications:

Intel(R) Core (TM) i3 5400 CPU;

2.1GHz x64-bit based processor;

64-bit Operating System (O.S);

8.00GB installed memory (RAM).

Modelling Software

The system was modelled using MATLAB Software 2021.The simulations code used in running the distribution load flow is shown in. Appendix C

Distribution Network System

Two different distribution networks were used in this research. The standard IEEE distribution networks for analysis and validation. Then applied to the GRA Lafia 15 Bus distribution network. The line and bus data for 33-bus standard IEEE radial distribution system will be adopted in this work as in Sarfaraz et al., (2017) and the work will be validated on the GRA Lafia 15-bus Government house feeder distribution system.

METHODS

Modelling and Simulation

Consider a multi-objective problem with m decision variables (parameters) and n objectives:

$$Minimize\ \ y=\left\{f_1(x), f_2(x),..., f_n(x)\right\} \tag{3.1}$$

$$\chi = [x_1, x_2, ..., x_m] \quad (3.2)$$

Where, x and y are the decision and objective vectors respectively.

Problem Formulation

Here, the objective is to accomplish two goals:

Minimize total active power loss, $P_{T(loss)}$

Minimize voltage deviation, V_D

The network total active power loss function as modelled in equation (2.11) is given by:

$$P_{T(loss)} = \sum_{ik=1}^{N_{Branch}} \left| I_{B(ik)} \right|^2 * \Re(Z_{ik}) \quad (3.3)$$

The voltage deviation function is expressed by:

$$V_D = \sum_{k=1}^{N_{Bus}} \left(V_k - V_k^{ref} \right)^2 \quad (3.4)$$

Where, V_k and V_k^{ref} are the per-unit (p.u) voltage values at bus k and the reference bus respectively.

The multi-objective function (J) can be formulated mathematically using the weighted sum of equation (3.3) and (3.4) to give:

$$min(J) = min\left(\omega_1 P_{T(loss)} + \omega_2 V_D\right) \quad (3.5)$$

Where, ω_1 and ω_2 are the weighting metrics used for adjusting the network total active power loss and voltage deviation functions respectively. Due to the equal importance attached to both objectives in equation (3.5), a unit weighting metric was assigned to both objective functions. Thus, $\omega_1 = \omega_2 = 1$.

Constraints

The optimal siting and sizing of DSTATCOM is considered as a constrained optimization problem that deals with the equality and inequality constraints.

Equality Constraints

The equality constraints represent the power flow equations expressed as:

$$\sum_{k=1}^{N_{Bus}} P_{Gk} - P_{Dk} = P_L \tag{3.6}$$

$$\sum_{k=1}^{N_{Bus}} Q_{Gk} - Q_{Dk} = Q_L \tag{3.7}$$

Where, P_{Gk} and Q_{Gk} are the total active and reactive power generation at bus k respectively,

P_{Dk} and Q_{Dk} are the total active and reactive power demand at bus k respectively,

P_L and Q_L are the total active and reactive power losses.

Inequality Constraints

The inequality constraints represent the network load bus, bus voltage and DSTATCOM size limits respectively given by:

$$\lambda_n^{\min} \le \lambda_n \le \lambda_n^{\max} \tag{3.8}$$

$$V_k^{\min} \le V_k \le V_k^{\max} \tag{3.9}$$

$$Q_n^{\min} \le Q_n \le Q_n^{\max} \tag{3.10}$$

The circuit representation for the DSTATCOM is shown in Figure 2 and the initial parameter settings for DSTATCOM and ABC algorithm are furnished in Table 1.

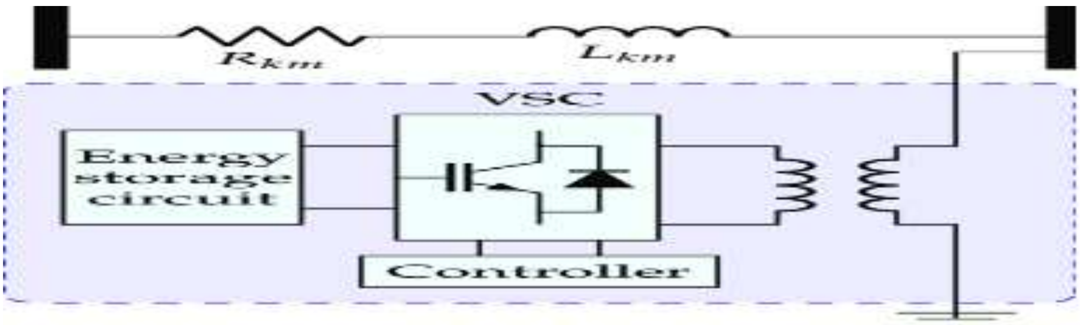

Figure 1: DSTATCOM Circuit Representation.

Table 1: Parameter settings for DSTATCOM and ABC algorithm

ABC Parameter	Value
Population of Bees	30
Population of Onlooker Bees	30
Maximum Iteration	100
Acceleration Coefficient	1

Experimental Flow Diagram

The study would explain the method followed to investigates the dynamic stability enhancement of the Abuja electricity distribution network_ government feeder Lafia, using Distribution Static Compensator (DSTATCOM). This can be explained using the block diagram in the experimental flow chart shown in Figure 1.

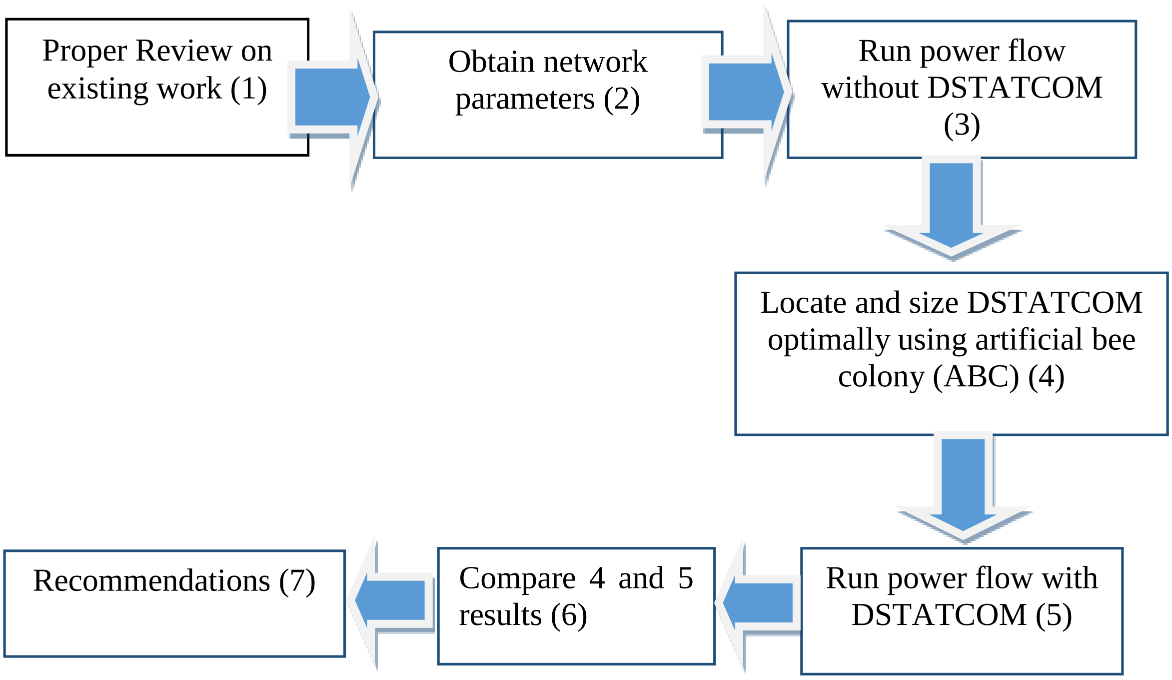

Figure 2: Experimental Flow Diagram

RESULTS COMPARISON AND REPRESENTATION

The results obtained from the optimal DSTATCOM placement and sizing at both IEEE 33-bus system and the Government house GRA 15-bus RDS will be presented through the following representations:

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Graphical representation (voltage profile improvement);

Bar chart representation (active power loss reduction);

Tabular representation (percentage active and reactive power loss minimized, bus location, etc.).

RESULTS

Results obtained during the simulation of the optimal placement of distributed Static Synchronous Compensator (DSTATCOM) for both the IEEE 33-bus and the Government-House 15-Bus distribution feeder systems is presented in this Chapter. The voltage profile with and without the distributed Static Synchronous Compensator is presented. Also, the real and reactive losses after running the simulation is are also presented. Results are presented in figures and tables, and then followed with the discussions of the results. The optimal location and sizing of the DSTATCOM for both distributions networks is determined using artificial bee colony optimization.

RESULTS FOR IEEE 33-BUS WITHOUT DSTATCOM

Voltage profile

Figure 2 shows the plot of the voltage profile obtained for IEEE 33-bus without the DSTATCOM installed. It can be seen from the figure that the highest value of 1 pu was obtained at bus while the minimum value of 0.9134 pu was obtained at bus 33. It can also be seen that 21 buses violated the allowed voltage where outside the allowed range of $\pm$ 0.95pu. It took about 1.3 seconds to run the simulation.

Power Loses without DSTATCOM

After running the load flow simulation for the IEEE bus 33 without DSTATCOM installed the real and reactive loses obtained is 201.77 kW and 134.99 kVar respectively. Figure 3 and 4 shows the real and reactive power losses obtained.

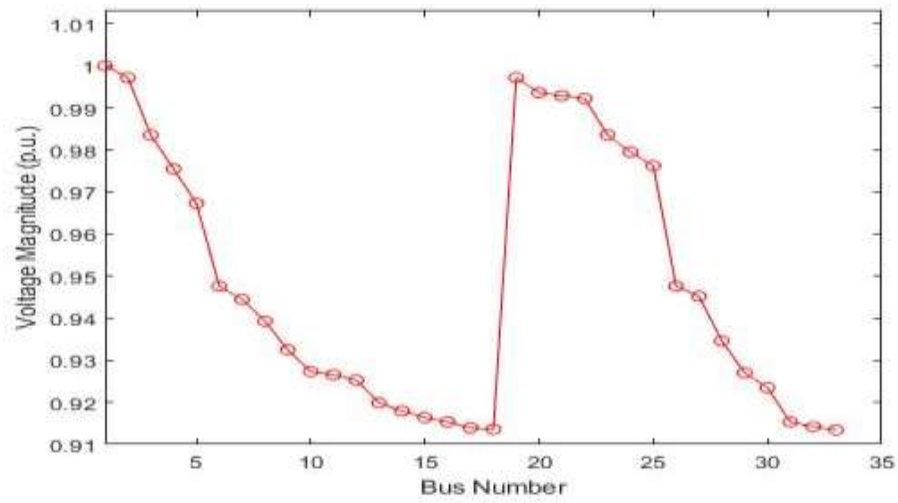

Figure 2: Voltage Profile for IEEE 33-Base Case

Figure 3 and 4 shows the real and reactive power loses at each of the 33 buses. Buses 3 and 6 have the highest real and reactive power losses. While, bus 18 and 22 have the lowest real and reactive power losses.

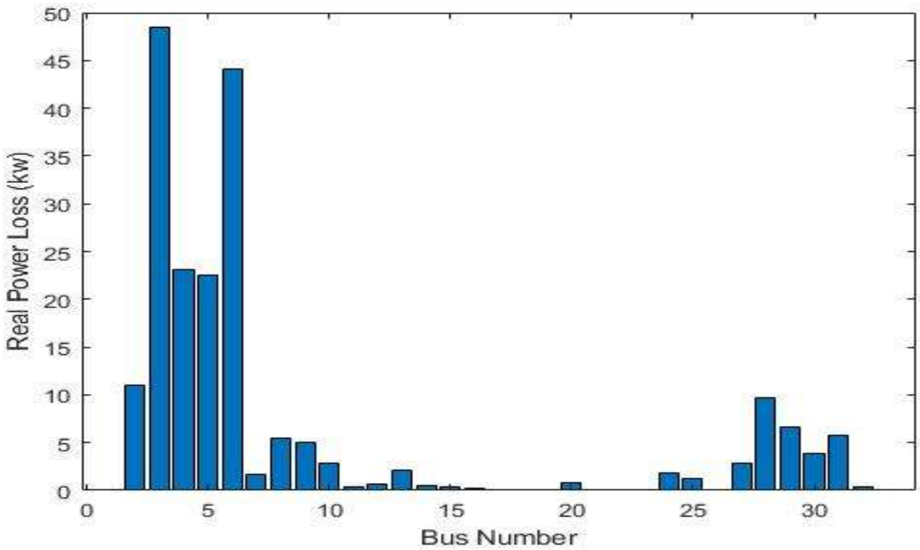

Figure 3: Real Power Loss for IEEE 33-Bus System

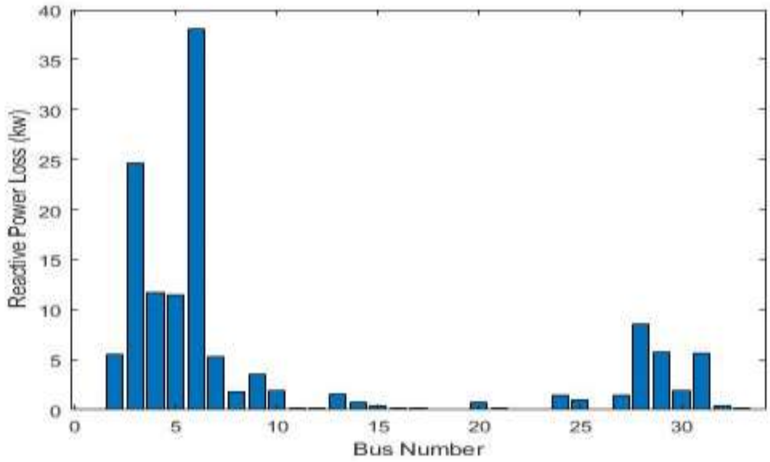

Figure 4: Reactive Power Loss for IEEE 33-Bus System

The real losses ass seen n figure 3 can occur in buses due to the resistance of the conductors and the electrical equipment connected to them. Reactive losses as seen in figure 4 can occur in buses due to the reactive power requirements of the loads connected to them. Reactive power is required by loads such as motors and transformers to maintain the required voltage levels and to improve their power factor. Both real and reactive losses result in a reduction in the efficiency of the power system and can lead to voltage drops and power quality issues.

RESULTS FOR IEEE 33 BUS SYSTEM WITH DSTATCOM INSTALLED

Location and Sizing

After running the simulation for the optimal sizing and placement of DSTATCOM on the IEEE 33-bus, results obtained show that the optimal location obtained is at bus 4. The optimal value obtained for the DSTATCOM is 1600 kVar. Figure 5 shows the convergence iteration curve of ABC for the optimal allocation of DSTATCOM in the IEEE 30-Bus network. Table 2 shows the values of total voltage deviation, mean average error and sum of square of errors obtained for IEEE without DSTATCOM installed and with DSTATCOM installed. As can be seen, the total voltage deviation, mean average error and sum of square of errors obtained with DSTATCOM is much smaller than those obtained without DSATCOM. This is implying that there is significant improvement in the performance with DTSATCOM installed.

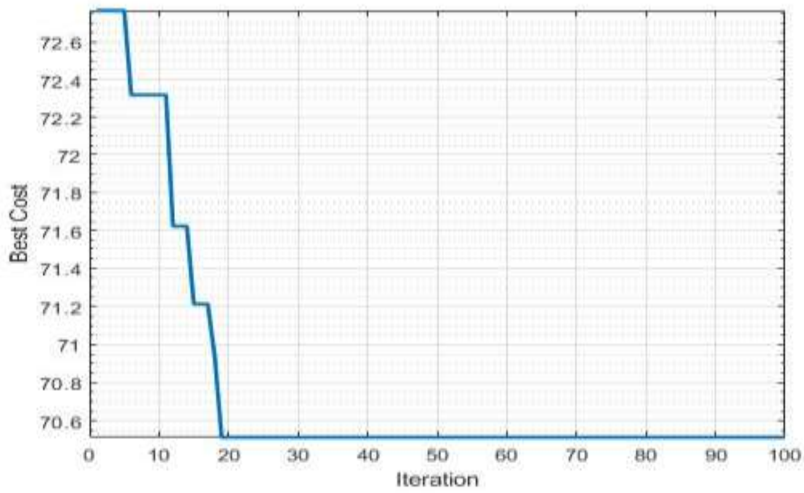

Figure 5: ABC Optimal DSTATCOM convergence iteration curve

The iteration curve for the plot as shown in Figure 5 converged as early as at the 19th iteration, after which there was no significant improvement n the results. This implies that we can set the maximum iteration at 50 improving the execution time of the program.

Table 2: Voltage Quality Performance

Performance Indices	IEEE 33	IEEE 34 + DSTAT
Total Voltage Deviation	1.7008	1.3461
MAE	0.0515	0.04079
SSE	0.1192	0.07447

Voltage Profile Improvement with DSTATCOM Installed

After simulation, Figure 6 shows the voltage profile plot obtained for IEEE 33-bus with DSTATCOM installed. It can be seen from the figure that the highest value of 1 pu was obtained at bus 1 while the minimum value of 0.9136 pu was obtained at bus 33. It can also be seen that 13 buses violated the constraints. (± 0.95pu). It took about 246 seconds to run the simulation. Figure 7 shows the plot for comparison of both with and without DSTATCOM installed.

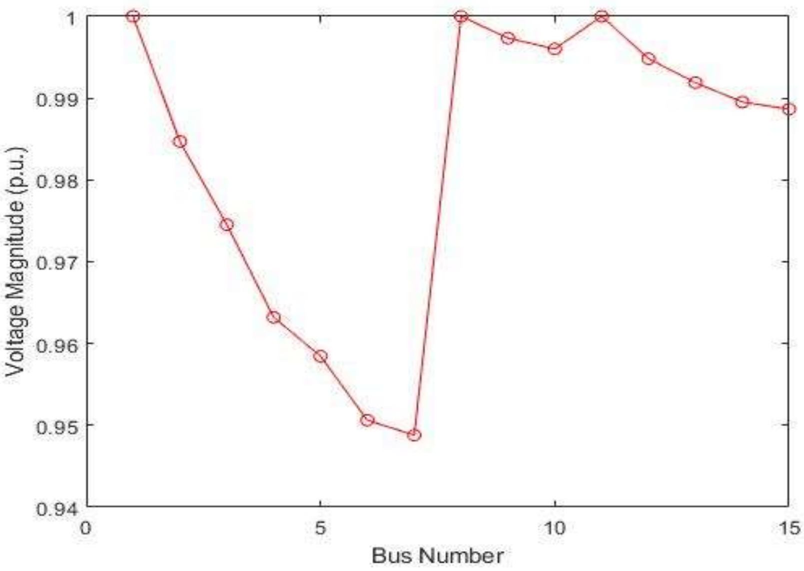

Figure 6: Voltage profile plot IEEE 33 bus with DSTATCOM

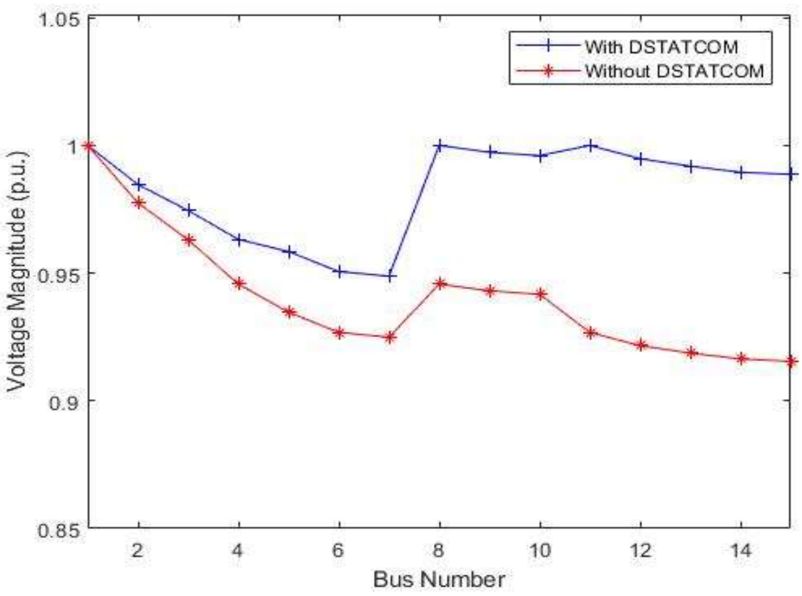

Figure 7: Comparison of voltage profile with and without DSTATCOM

DISCUSSIONS

The total voltage deviation, mean average error and sum of square of errors obtained for the IEEE 33bus RDS is 1.7008, 0.0515 and 0.1192 respectively. With DSTATCOM, installed the total voltage deviation, mean average error and sum of square of errors obtained for the

GRA 15 bus RDS is 1.3461, 0.04079 and 0.07447respectively. The values obtained for the IEEE 33bus RDS with DSTATCOM installed is much lower than without the DSTATCOM installed. From the plots, It can clearly be seen that there that there is a significant improvement in the quality of voltage which is as a result of the installation of the DSTATCOM.

From results obtained and shown table 3 and Figure 7. It can be clearly seen that the DSTATCOM improved the voltage profile of the whole feeder system. There was 13 bus voltages violation when the DSTATCOM was installed as compared to 21 bus violations when the DSTATCOM was not installed. The lowest voltage at the bus without the DSTATCOM was at bus 33 at 0.9134pu. After optimal DSTATCOM installation the bus voltages improved and the new minimum voltage was at bus 0.9244pu at bus 18. This is within the allowable range of $\pm$ 1.05pu. The highest voltages for both cases were 1pu @ bus 1.

Power Loses Reduction with DSTATCOM Installed

After running the load flow simulation for the IEEE bus 33 with DSTATCOM installed the real and reactive loses obtained is 148.05kw and 98.93kvar respectively. Figure 8 shows the real losses and reactive loses obtained. Figure 8 shows the comparison of the real loses at each bus with and without DSTATCOM installed. And Figure 9 shows the comparison of the reactive loses at each bus with and without DSTATCOM installed.

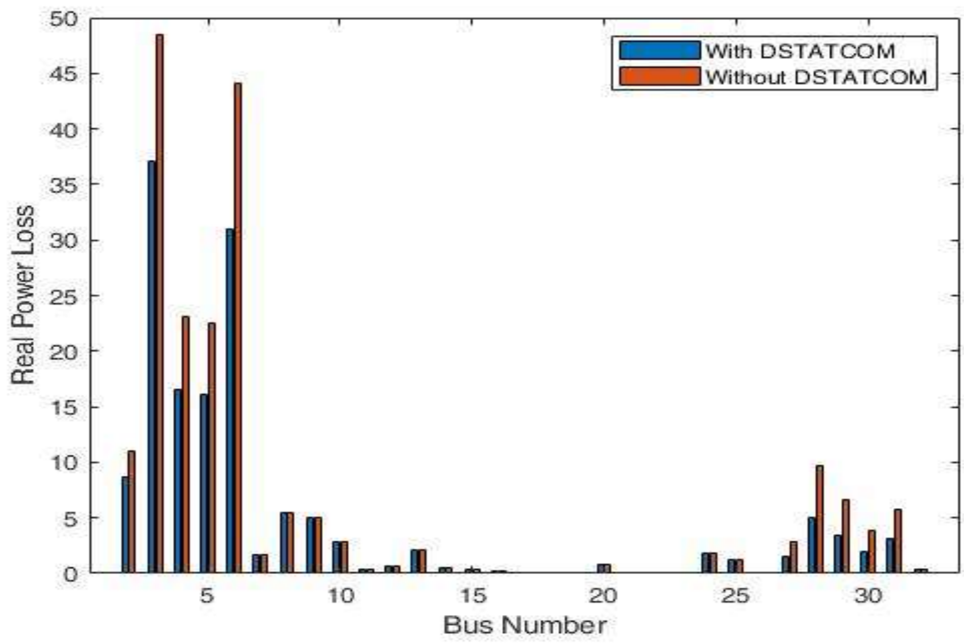

Figure 8: Real Power Loss for IEEE 33 RDS With and Without DSTATCOM Installed

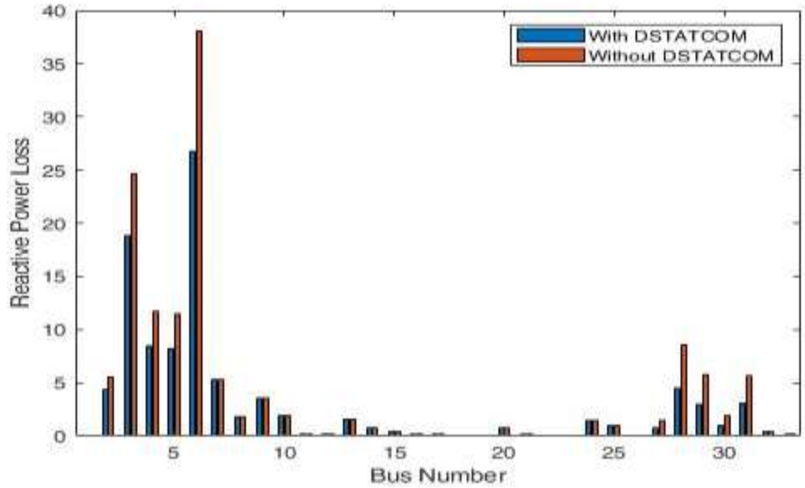

Figure 9: Reactive Power Loss Comparison for IEEE 33 Bus system

Discussions

The real power Loss obtained before DSTATCOM installation is 201.77kw. After DSTATCOM installation a loss of 148.05kw was obtained. This represents a 26.6% reduction in real power loss across the RDS, which is a significant improvement. Similarly, the reactive power loss obtained before DSTATCOM installation is 134.99kvar. With DSTATCOM installation the reactive power loss reduced to 98.93 kvar. This also represents a 26.7% reduction in reactive power loss across the RDS. This loss reduction achieved because of the optimal placement and sizing of the DSTATCOM on the RDS.

Table 3: Comparison of Results for IEEE 33 Bus System with and without DSTATCOM

Parameters	Base Case Without DSTATCOM	With DSTATCOM
Real Power Loss	201.77kw	148.05 kw
Reactive Power loss	134.99kvar	98.93 kvar
Bus Max Vpu	1 @ Bus 1	1 @ Bus 1
Bus Min Vpu	0.9134pu @ Bus 33	0.9244pu @ Bus 18
Number of Bus Violations	21	13
DSTATCOM Location	-	30
Percentage reduction in P Power Loss	-	26.6%

Percentage reduction in Q Power Loss	-	26.7%
Optimal Val of DSTATCOM	-	1200kvar
elapsed Time	0.105s	273s

RESULTS FOR GOVT-HOUSE 15 BUS FEEDER WITHOUT DSTATCOM INSTALLED

Voltage profile

Figure 9 shows the voltage profile obtained for Govt-House 15 Bus Feeder without the DSTATCOM installed. It can be seen from the figure that the highest value of 1 pu was obtained at bus 1 while the lowest value of 0.9155 pu was obtained at bus 15. It can also be seen that 12 buses violated the allowed voltage range because they are outside the allowed range of + 0.95 pu. It took about 0.5 seconds to run the simulation.

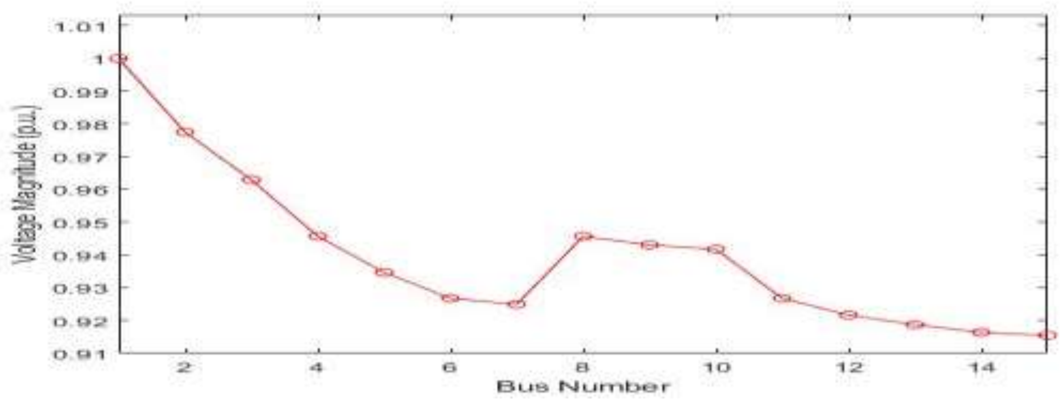

Figure 10: Voltage Profile for Govt-House Feeder without DSTATCOM

Power Loses Without DSTATCOM Installed

After running the load flow simulation for the Govt-House 15 Bus Feeder without DSTATCOM installed the real and reactive loses obtained is 171.66 kW and 195.47 kVar respectively. Figure 11 shows the real and reactive losses obtained on same plot. The real and reactive loses are highest on bus 2 and lowest at bus 9.

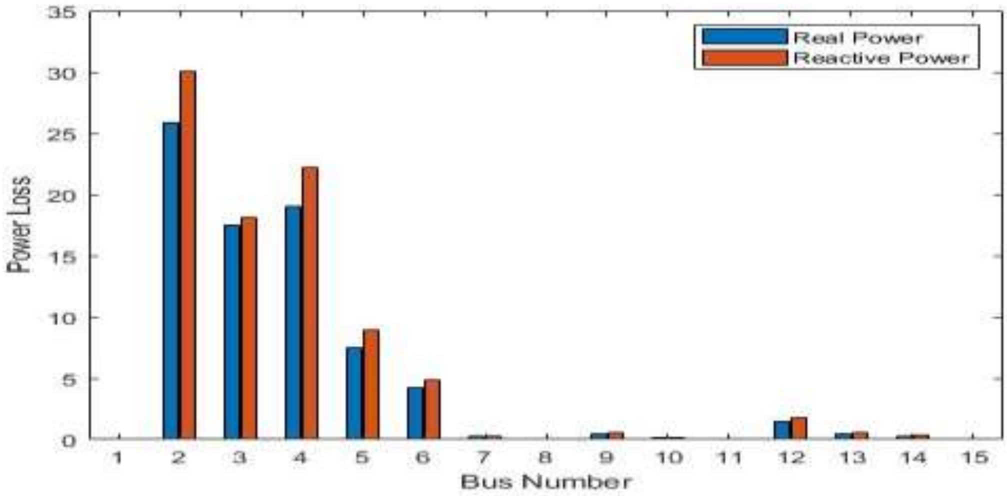

Figure 11: Real and Reactive Losses at Govt-House Feeder without DSTATCOM

RESULTS FOR GOVT-HOUSE 15 BUS FEEDER WITH DSTATCOM INSTALLED

Location and sizing

The results obtained after running the artificial bee colony algorithm simulation for the optimal sizing and placement of DSTATCOM on the Govt-House 15 bus show that the best location for placement of DSTATCOM is at Bus 4. The artificial bee colony algorithm arrived at an optimal size of 629.5 kVar for the DSTATCOM. This can be seen in the voltage profile improvement and reduction n the loss along the Govt-House 15 bus radial distribution system

Voltage Profile Improvement with DSTATCOM Installed

Figure 12 shows the plot of the voltage profile obtained for Govt-House 15 Bus RDS with DSTATCOM installed. It can be seen from the figure that the highest value of 1 pu was obtained at bus while the minimum value of 0.9488 pu was obtained at bus 7. It can also be seen that there was only one bus that violated the constraints. (± 0.95pu). Figure 13 shows the plot for comparison of both with and without DSTATCOM installed.

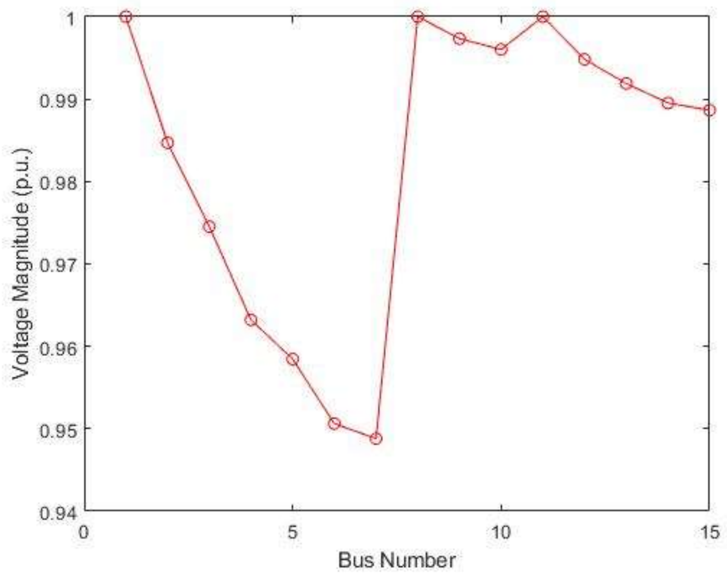

Figure 12: Voltage Profile for Govt-House 15 Bus feeder with DSTATCOM installed

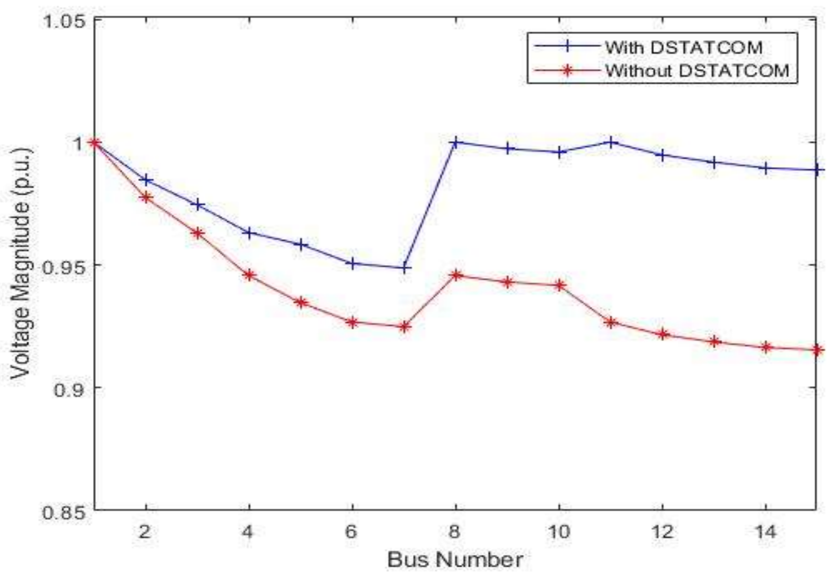

Figure 13: Voltage Profile Comparison for Govt-House 15 Bus feeder with DSTATCOM installed

Table 4 show the voltage quality performance for the RDS. The total voltage deviation, mean average error and sum of square of errors obtained for the GRA 15 bus RDS is 0.8979, 0.0599 and 0.0619 respectively. With DSTATCOM, installed the total voltage deviation, mean average error and sum of square of errors obtained for the GRA 15 bus RDS is 0.2616, 0.01744 and 0.0094 respectively. The values obtained for the RDS with DSTATCOM installed is much lower than without the DSTATCOM installed. This indicates that there is an overall significant improvement in the quality of voltage which is as a result of the installation of the DSTATCOM.

Table 4: Voltage Quality Performance

Performance Indices	GRA 15	GRA 15 + DSTAT
Total Voltage Deviation	0.8979	0.2616
MAE	0.0599	0.0174
SSE	0.0619	0.0094

Discussions

From results shown in Table 4 and Figure 13. It can be clearly seen that the DSTATCOM improved the power quality of the whole Govt-House 15 Bus feeder system. There was only one bus voltages violation after the DSTATCOM was installed as compared to 12 bus violations when the DSTATCOM was not installed. The lowest voltage at the bus without the DSTATCOM was at bus 7 at 0.9155 pu. After optimal DSTATCOM installation the bus voltages improved and the new minimum voltage was at bus 0. 0.9488 pu at bus 7. All the bus voltage except bus 7 fall within the allowable range of $\pm$ 1.05pu. The highest voltages for both cases were 1pu @ bus 1.

Power Loses Reduction with DSTATCOM Installed

After running the load flow simulation for the Govt-House 15 Bus feeder with DSTATCOM installed the real and reactive loses obtained is 61.87 kw and 70.35 kVar respectively. Figure 14 shows the real losses and reactive loses obtained. Figure 15 shows the comparison of the real loses at each bus with and without DSTATCOM installed. And Figure 9 shows the comparison of the reactive loses at each bus with and without DSTATCOM installed. Figure 10 shows the comparison of the total loses.

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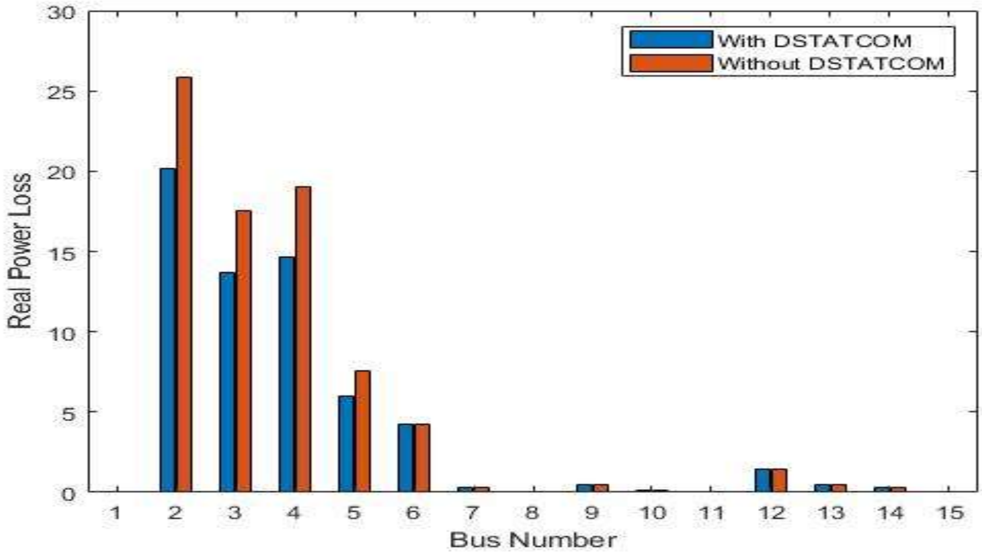

Figure 14: Real Power Loss Comparison for Govt-House 15 Bus feeder with DSTATCOM installed

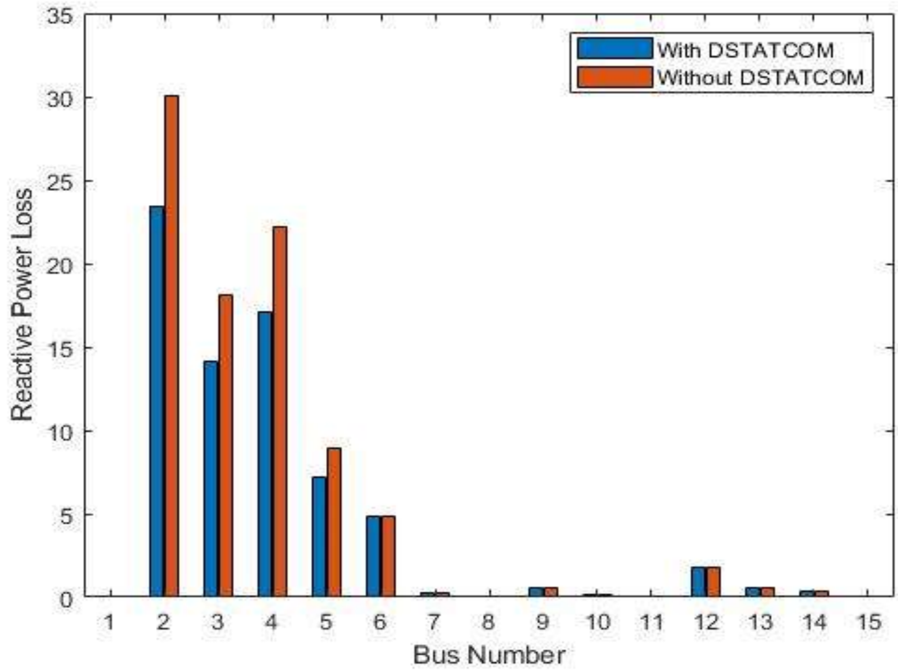

Figure 15: Reactive Power Loss Comparison for Govt-House 15 Bus feeder with DSTATCOM installed

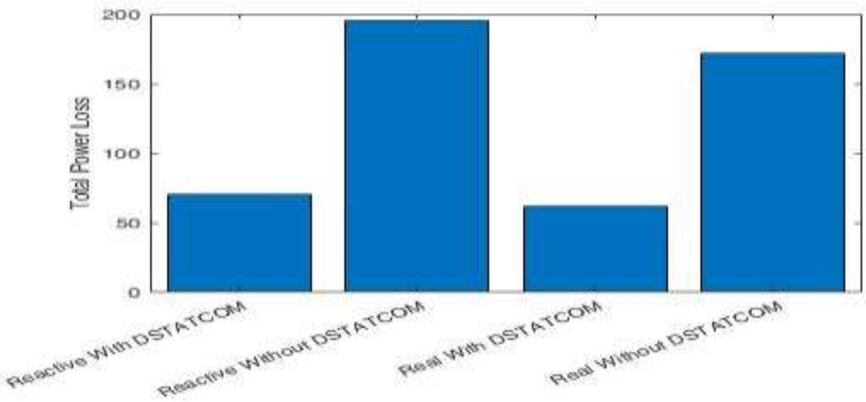

Figure 16: Total Power Comparison for Govt-House 15 Bus feeder with DSTATCOM installed

Discussions

At the Govt-House 15 Bus, the real power Loss obtained before DSTATCOM installation is 171.65 kW. After DSTATCOM installation a loss of 61.87 kW was obtained. This represent 63.9% reduction in power loss across the RDS, which is a significant improvement. Similarly, the reactive power loss obtained before DSTATCOM installation is 195.47 kVar. With DSTATCOM installation the reactive power loss dropped to 70.35 kVar. This also represents 64.01% reduction in reactive power loss across the RDS. This loss reduction achieved because of the optimal placement and sizing of the DSTATCOM on the RDS.

Table 5: Comparison of Results for Govt-House Feeder with and without DSTATCOM

Parameter	Base Case Without DSTATCOM	With DSTATCOM
Real Power Loss	171.65 kw	61.87 kw
Reactive Power loss	195.47 kvar	70.35 kvar
Bus Max Vpu	1@ Bus1	1@ Bus1
Bus Min Vpu	0.9155 @ Bus 15	0.9411@ Bus 7
Number of Bus Violations	12	1
DSTATCOM Location	--	Bus 4
% Reduction in Real Power Loss	--	63.9%
% Reduction in Reactive Power Loss	--	64.01%
Optimal Val of DSTATCOM	--	629.05 kvar
elapsed Time	0.4s	101s

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CONCLUSION

This work presented the application of Artificial Bee Colony (ABC) for the optimal DSTATCOM siting and sizing in Radial Distribution Systems (RDS) for power loss minimization and voltage profile improvement. The IEEE 33 Bus Radial distribution system and the 15 bus Government feeder Lafia of the Abuja electricity distribution network has been modelled in Matlab environment. The one-line diagram line data and bus data is presented in the appendix. The RDS power flow analysis was modelled using the Bus Injection to Bus Current matrix (BIBC).

The models have been simulated without DSTATCOM installed and also with DSTATCOM installed. The optimal location and sizing of the DSTACOM was done using Artificial Bee Colony (ABC) Optimization techniques.

The active power loss and bus voltage deviation of the radial distribution was included in the formulation of the multi-objective function and used in the ABC approach. The approach has been demonstrated on Standard IEEE 33-bus Radial Distribution System to check its effectiveness and then applied to the 15 bus Government feeder Lafia of the Abuja electricity distribution network. The results obtained from application of ABC with optimal siting and sizing of DSTATCOM shows that the system voltage profile has improved and the power losses minimized. The results demonstrate the great ability of DSTATCOM to regulate the voltage profile underline loss minimization condition in radial distribution system. The loss comparison table shows that DSTATCOM can reduce both the active as well as reactive losses at the same time.

In the Standard IEEE 33-bus RDS, the DSTATCOM was sited at bus 4 with a total maximum size of 1200kvar. There was an overall voltage improvement with ABC, and a system power loss reduction of 26.6% and 26.7%for real and reactive power respectively.

The ABC algorithm was also used to determine the optimal location and size for the 15-bus, 11 kV Govt-House feeder RDS in Lafia, Nigeria. The DSTATCOM was optimally sited using ABC between at 4 with a maximum DTSATCOM size of 629.05 kvar. There was an overall voltage improvement with ABC and this caused a system total real and reactive power loss reduction of 63.9% and 64.01% for real and reactive power respectively. Result presented in discussions, tables and figures clearly show the effectiveness and superiority of the proposed ABC algorithm to improve the quality of power delivered by improving voltage profile and reducing power loss.

RECOMMENDATIONS FOR FURTHER WORK

For further research works, the following are recommended:

In this work the sole optimization goal was loss reduction, within voltage constraints. Voltage can also be incorporated in to the optimization equation.

Investigating the performance of hybrid ABC with other meta-heuristic techniques to reduce execution time and improve results in very large radial distribution system.

Investigating the performance of hybrid ABC with other meta-heuristic techniques to reduce execution time and improve results in very large radial distribution system.

CONTRIBUTIONS TO KNOWLEDGE

This is the first time the artificial bee colony algorithm will as used to determine the optimal siting and sizing of the DSTATCOM on the Govt-House 15 Bus radial distribution system in Lafia, Nasarawa State, Nigeria.

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