



VOLTAGE STABILITY ENHANCEMENT BY OPTIMAL SIZING AND SITING OF STATIC SYNCHRONOUS COMPENSATOR USING DRAGONFLY ALGORITHM



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ABSTRACT

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Ever- increasing demand of electric power makes transmission networks operate outside their voltage stability limits. To meet with the demand, the networks have to be improved, which may be difficult due to economic, environmental impact and implementation period. Therefore, Flexible Alternating Current Transmission Systems (FACTS) devices are employed to achieve proper utilization of existing transmission networks. This research work has presented the application of Dragonfly Algorithm (DA) by optimal sizing and siting of STATCOMs for voltage stability enhancement. The simulation was carried out using Newton Raphson Power Flow technique in MATLAB 2018a environment. The DA was implemented on 52-Bus Nigerian transmission network, where STATCOMs were optimally placed at buses 6 (Ikeja West), 18 (Alaoji), 22 (Makurdi), 23 (B/Kebbi), 25 (Oshogbo), 34 (Maiduguri), 43 (Sakete), 45 (Jalingo), 48 (Kano) and 52 (AES) with optimal sizes of 47.3 MVar each after 18 iterations. The obtained VPEI was found to be 1.1126, which signifies enhancement in voltage stability of 11.26%.

1. INTRODUCTION

Power quality refers to “Maintaining the nearly sinusoidal waveform of bus voltages and current at rated magnitude and frequency” [1]. Poor power quality results in undesirable effects which include; short interruptions, voltage swell and sag, transients etc. But voltage instability among others is the issue that affects power systems most even at steady-state [2]. To determine the instability in a power system, several methods of power flow analysis are involved among which is power flow study [3]. Power flow analysis is very important in planning, economic operation, load scheduling and exchange of power between utilities [4]. It is also aimed to ensure that electrical power transfer from generating plants to consumers via the interconnected system is cheap, reliable and stable [5].

The power flow equations can be solved using iterative techniques such as; Gaussian elimination method, Gauss-Siedel methods (GS) and Newton Raphson (NR) methods among others [6]. But Newton Raphson technique is the most preferred due to its quadratic convergence characteristics compared to GS and GE methods [7]. Transmission systems are subjected to voltage instabilities which limit the amount of power that can be transmitted.

Therefore, the need for effective voltage control becomes vital on transmission systems using FACTS namely: Static Var Compensator (SVC), Static Synchronous Series Capacitor (SSSC), Thyristor Control Series Capacitor (TCSC), Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM) etc [8].

FACTS devices have faster response time and lower maintenance costs as compared to the conventional methods such as automatic generation control, excitation control, transformer tap-changer control

and phase-shifting transformers [9]. An improvement of voltage stability is achieved through optimal location of FACTS devices, which can be carried out using the emerging optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Dragonfly Algorithm (DA) etc. Several researchers worked on system voltage stability enhancement using Static Synchronous Compensator.

In [7], Kaily and Brar emphasized on the optimal placement of STATCOM for the reduction of power losses and improvement of VP. This conventional intuition-based manual placement search lead to local optimum results. In [18], Radman and Rashman determined only the optimal location of STATCOM by improvement of the VP as the decisive factor. The influence of STATCOM on the nodal voltages that were far away from the candidate bus was not significant. The sizing of the device was also not considered, to provide a clear economic feasibility of the device to be incorporated. This research work adopted the use of Newton Raphson technique for the power flow analysis by optimal sizing and siting of STATCOM using DA for system voltage stability enhancement. The approach is implemented on the 52-bus 330kV Nigerian transmission network in MATLAB R2018a environment.

2. STRUCTURE OF 52-BUS 330KV NIGERIAN TRANSMISSION NETWORK

The Nigerian transmission network comprises of seventeen generating stations, Fifty-Two buses and Sixty-Four transmission lines. It is classified into three major parts namely; the North, West and the East part. It has four control centers, one National Control Center (NCC) at Oshogbo and threesupplementary control centers at Benin, Shiroro and Egbin [10]. The single line diagram of the network is shown in Figure 1. The voltages of all load and generator buses have been constrained within the limits of 0.95p.u to 1.05p.u, considering a base power and voltage of 100MVA and 330kV [11].

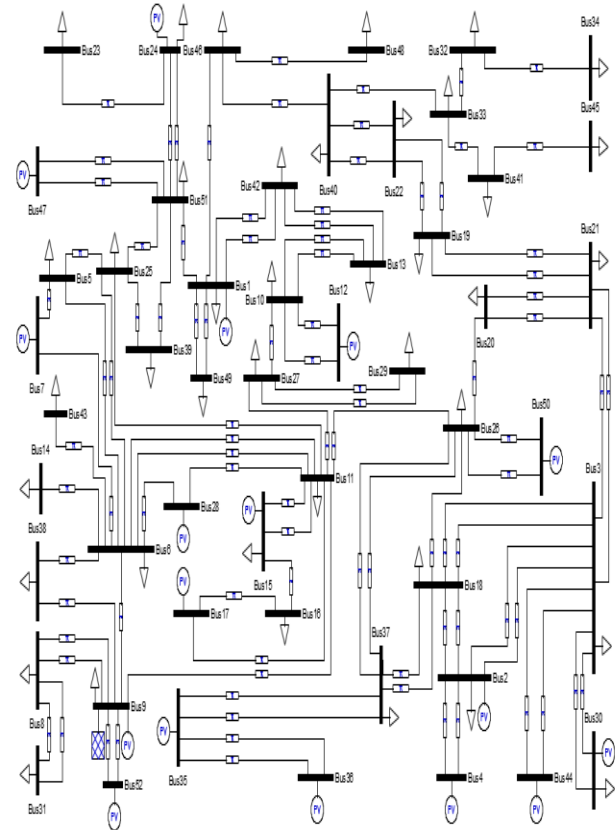


Fig.1. Single line diagram of 52-bus 330kV Nigerian transmission network

3. POWER FLOW ANALYSIS

Power flow analysis is defined as the study of various numerical methods for solving power system non-linear equations formulation. It is very important in planning, economic operation, load scheduling and exchange of power between utilities [3]. Newton-Raphson technique works faster and guarantees convergence. Its flow chart is shown in Figure 2. Two equations are duly observed for each load bus, given by equations (1) and (2).

Active injected power

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

Reactive injected power as

$$Q_i = - \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \quad (2)$$

Expanding equations (1) and (2) result in linearized Jacobian matrix given by equation (3)[12].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (3)$$

Where J_1, J_2, J_3 and J_4 are elements of Jacobian matrix. ΔP and ΔQ are the active and reactive power mismatches. $\Delta |V|$ is the magnitude of bus voltages, $\Delta \delta$ is the phase angle of bus voltages. [13].

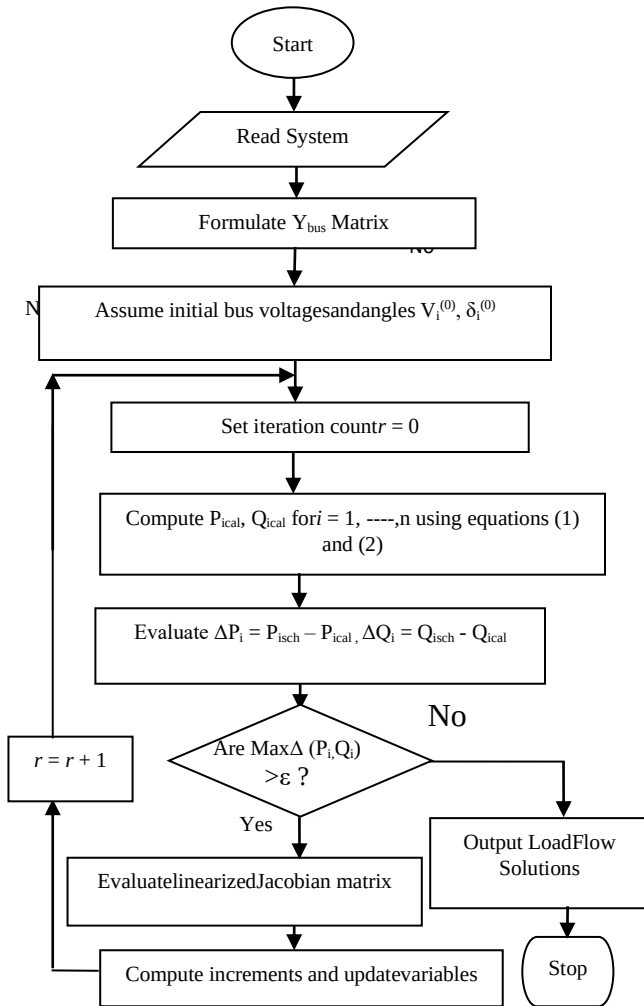


Fig.2. Flow Chart of NRLF Technique

4. STATIC SYNCHRONOUS COMPENSATOR

STATCOM is a shunt connected reactive power controlling device capable of supplying or absorbing the reactive power whose output can be altered to

control the required parameters (voltage, phase angle, impedance etc.) of a power system.

STATCOM comprises of a three-phase Voltage Source Inverter (VSI), d.c capacitor, reactor and a transformer to match the line voltage. The output voltage is supplied by the inverter which is linked with the AC-supply via link inductor as shown in Fig 3. If the output voltage E_s is higher than the system bus voltage, E_t then current flows through the reactance from the VSI to the a.c system and supplies capacitive reactive power to the a.c system. Otherwise, the current flows from the a.c system to the VSI and absorbs inductive reactive power from the a.c system. The essence of d.c capacitor is to stabilize the controlled d.c voltage required for the operation of the VSI [14].

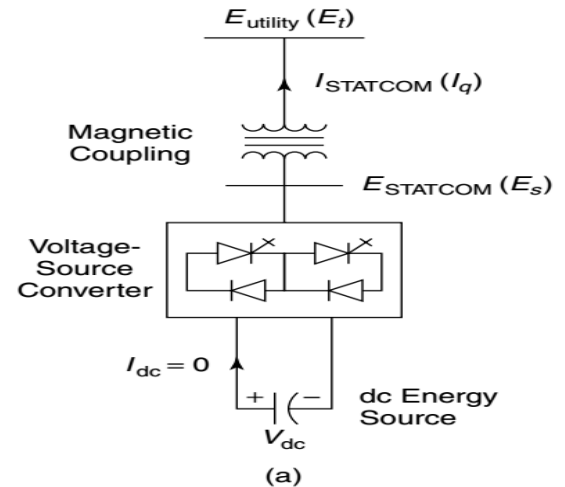


Fig.3. STATCOM Power Circuit

4.1. STATCOM performance capabilities

STATCOM enhances power system performance in such areas:

- Transmission and distribution systems dynamic voltage control;
- Damping of the power- systems oscillations;
- Voltage flicker control;
- Transient stability and
- Control of active and reactive power etc [15].

4.2 Power flow Model of Static Synchronous Compensator

Fig. 4 depicts the circuit model of STATCOM incorporated to Bus i of an N -Bus power system; the subscript 'p' stands for STATCOM connected in

parallel with bus i of the power system. The STATCOM is modeled as a controllable voltage source (E_p) in series with impedance.

The real part of this impedance represents the ohmic losses of the VSI devices and the coupling transformer, whereas the imaginary part of this impedance explains the leakage reactance of the coupling transformer [16].

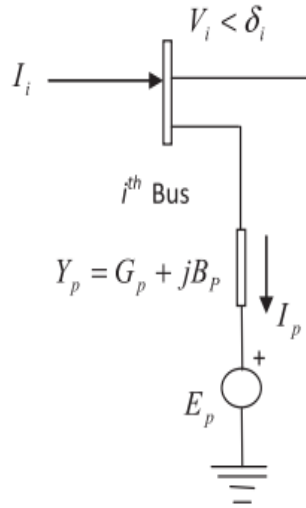


Fig.4. Steady State Model of STATCOM

The STATCOM voltage source is given by [17].

$$V_p = E_p(\cos \delta_p + j \sin \delta_p) \quad (4)$$

The load flow equations of the system with STATCOM connected to bus i , are equal as equations of the base case for all buses and given by Equations (1) and (2), except for the bus to which device is incorporated and are given by equations (5) and (6) [18]:

$$P_m = P_p + \sum_{k=1}^n |V_i||V_k||Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) \quad (5)$$

$$Q_m = Q_p + \sum_{k=1}^n |V_k||Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \quad (6)$$

Where

$$P_p = G_p|V_i|^2 - |V_m||E_p||Y_p| \quad (7)$$

$$Q_p = -B_p|V_i|^2 - |V_{ip}||E_p||Y_p| \quad (8)$$

The active power equation needed to solve the load flow problem is given by equation (9) [16].

$$P_{Ep} = -G_p|E_p|^2 + |V_{ip}||E_p||Y_p| \quad (9)$$

Where P_{Ep} is the power consumed by the source of STATCOM, V_{ip} is the voltage at the i^{th} bus; Y_p is the admittance of the STATCOM; G_p , B_p are the conductance and susceptances of the STATCOM; θ_p is the admittance angle of transmission line connected between the i^{th} and k^{th} bus respectively; δ_p is the voltage source angle of the STATCOM and E_p is the voltage source of STATCOM converter.

5. PROBLEM FORMULATION

STATCOM device is optimally placed to enhance the voltage stability using DA, and certain criteria are followed on some fitness objective function, subject to some constraints which include bus voltage magnitudes, STATCOM device, lines power ratings, active and reactive power limits of generators.

5.1. Objective function

The Objective function for this work is mathematically formulated as:

$$J = \text{Max} \sum_{i=1}^{i=0 N_B} F(V_B) \{SSC(C_{SSC}, N_{SSC})\} \quad (10)$$

J Describes the fitness function to be optimized; $F(V_B)$ represents the violation function of bus voltage; N_B is the number of buses in the system. C_{SSC} denotes capacity of STATCOM device and N_{SSC} represents bus location of STATCOM device

$$F(V_B) = 0 \quad \text{if } 0.95 \leq V_i \leq 1.05 \quad (11)$$

Otherwise

$$F(V_B) = \log \varphi(F(V_B) * \text{abs} \left[\frac{V_{i(nominal)} - V_i}{V_{i(nominal)}} \right] * \left[\frac{1}{lin} \right]) \quad (12)$$

$\varphi(F(V_B))$ Denotes the index value percentage of the bus voltage against the allowable limit; $V_{i(nominal)}$ is the nominal voltage magnitude at bus i ; V_i is the voltage magnitude at bus i .

lin defines the integer coefficient to regulate voltage variations.

5.2. Constraints

The J presented in equation (10) is maximized subject to both equality and inequality constraints as follows;

5.2.1. Equality constraints:

$$P_L = P_G - P_D(V, \delta) \quad (13)$$

P_L Denotes the real power loss, P_G represents the real power generation and P_D is the real power demand.

$$Q_L = Q_G - Q_D(V, \delta) \quad (14)$$

Q_L Depicts the reactive power loss, Q_G represents the reactive power generation and Q_D is the reactive power demand.

5.2.2. Inequality constraints:

Power limits of generators;

$$P_{Gi}^{Min} \leq P_{Gi} \leq P_{Gi}^{Max} \quad (15)$$

$$Q_{Gi}^{Min} \leq Q_{Gi} \leq Q_{Gi}^{Max} \quad i = 1, 2, 3 \dots n_G \quad (16)$$

Bus voltages limits;

$$V_i^{Min} \leq V_i \leq V_i^{Max} \quad (17)$$

Power flow limits;

$$P_{iK} \leq P_{iK}^{Max} \quad (18)$$

$$V_{sh}^{Min} \leq V_{sh} \leq V_{sh}^{Max} \quad (19)$$

6. PROPOSED DA ALGORITHM

Dragonfly Algorithm (DA) is emerging meta-heuristics swarm intelligence based optimization technique that originates from the swarming behaviors of dragonflies in nature used for solving single and multi-objective optimization issues. When Dragonflies create sub-swarms and fly over different areas in a static swarm is called exploration phase and when flies in bigger swarms and along one direction, is referred to as exploitation phase [19].

6.1 Operators for exploration and exploitation phases.

The three operators which swarms behave are;

- Separation- Refers to the static collision avoidance of individuals from one another in the neighbourhood.
- Alignment- Denotes to the velocity matching between individuals in the neighbourhood.
- Cohesion- Means the tendency of individuals towards the centre of the mass of the neighbourhood [20].

6.2 DA Updating factors

The major target of any swarm is survival, so all of the individuals should move towards food sources and migrated from enemies. Looking at these behaviours, there are five factors to be considered in updating individuals in swarms [20]. Each of the aforementioned behaviours has its own mathematical model as follows: The separation is given by equation (20):

$$S_i = - \sum_{j=1}^N X - X_j \quad (20)$$

X Denotes the position of the current individual. X_j Defines the position of j -th neighbouring individual and N is the number of neighbouring individuals.

Alignment is modeled as

$$A_i = \frac{\sum_{j=1}^N V_j}{N} \quad (21)$$

Where X_j denotes the velocity of j-th neighbouring individual
The cohesion is calculated as

$$C = \frac{\sum_{j=1}^N X_j}{N} - X \quad (22)$$

Attraction towards a food source is given by

$$F_i = X^+ - X \quad (23)$$

Where X^+ depicts the position of the food source.

And distraction from enemy is calculated as:

$$E_i = X^- + X \quad (24)$$

X^- Shows position of the enemy.

6.3. Step vector

The step vector shows the direction of the movement of the dragonflies and expressed as follows:

$$\Delta X_{t+1} = (sS_1 + aAX_i + cC_{il} + fF_i + eE_i) + w\Delta X_i \quad (25)$$

where s is the separation weight, S_1 denotes the separation of the i-th individual, a means alignment weight, A_i represents alignment of i-th individual, c shows the cohesion weight, C_i is the cohesion of the i-th individual, f indicates the food factor, F_i is the food source of the i-th alignment weight A_i individual, e is the enemy factor, E_i stands for the position of enemy of the i-th individual, w is the inertia weight, and finally t which means the iteration counter.

6.4 Position vector

This determines the current location of the swarm and calculated as follows:

$$X_{t+1} = X_t + \Delta X_{t+1} \quad (26)$$

t stands for the current iteration.

In situation where there are no neighbouring solutions, dragonflies use random walk (Le'vy flight) to enhance the stochastic behaviour of the dragonflies which is updated using equation (27) [21].

$$X_{t+1} = X_t + Le'vy(d) \times X_t \quad (27)$$

d is the dimension of the position vectors.

Le'vy flight is given by

$$Le'vy(x) = 0.01 \times \frac{r_1 \times \sigma}{|r_2|^{\frac{1}{\beta}}} \quad (28)$$

r_1, r_2 are two random numbers in (0, 1), β is typically constant =1.5, and σ is expressed as:

$$\sigma = \left(\frac{\Gamma(1 + \beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right)^{1/\beta} \quad (29)$$

7. VOLTAGE PROFILE ENHANCEMENT INDEX (VPEI)

FACTS devices offer significant contributions toward enhancing voltage stability of the network. Hence, the device benefits to the system are measured considering upper V^U and lower (V^L) voltage magnitudes of the simulated results obtained at base case with those presented at optimal scenario. Taking this philosophy into account, VPEI is employed [22]. The nominal voltage V^{nom} and voltage profile V_p at k^{th} bus are determined as describe in equations (30) and (31).

$$V^{nom} = \frac{(V^U + V^L)}{2} \quad (30)$$

$$V_{p_k} = \frac{4(V_{Kk} - V^L)(V^U - V_k)}{V^U + V^L} \quad (31)$$

The Voltage Profile Index is given by:

$$VPI = \frac{1}{N_B} \sum_{k=1}^{N_B} VP_k (32)$$

VP_k Is the voltage profile at k^{th} bus, N_B depicts the total number of load buses in the system.

The VPEI is therefore expressed as:

$$VPEI = (VPI_{\text{WithSSC}})/(VPI_{\text{WithoutSSC}}) (33)$$

If the VPEI is greater than unity, it signifies enhancement in voltage profile. If the VPEI is less than unity, it indicates deterioration of voltage profile. If the VPEI is unity, it denotes no effect of the device.

8. IMPLEMENTATION PROCEDURE

A MATLAB based program is employed for the power flow analysis of the 52-Bus 330kV Nigerian transmission network without and with STATCOM incorporated. The input data collected from NCC includes: number and types of buses, line, generation, load as well as STATCOM control parameters. STATCOM is modeled as generator source, which is capable of injecting or absorbing reactive power, to comprehend the voltage instability of the system. The performance of proposed DA method is compared with base case scenario. 50 independent trials are made. The trial that gives the best solution is selected as the desired parameter for the proposed work. In this work, two convergence criteria are laid down:

- i. Maximum number of iterations set.
 - ii. If there is no enhancement in the OF, the program terminates after ten best iterations.
- Finally, the effect of STATCOM on the network is determined through VPEI.

9. RESULTS AND DISCUSSION

The simulation results for the power flow analysis of the network are performed for both base case and optimal scenarios, where the results of voltage profiles to the network are presented in Figure 5. The results show voltage profile of the network buses without

STATCOM device, it can be observed that voltages at buses 22, 23, 32, 33, 34, 40, 41, 43, 45, 46 and 48 (i.e. Makurdi, B/Kebbi, Damaturu, Gombe, Maiduguri, Jos, Yola, Sakete, Jalingo, Kaduna and Kano) are 0.9407p.u, 0.9306p.u, 0.8073p.u, 0.8345p.u, 0.7824p.u, 0.9384p.u, 0.8120p.u, 0.8797p.u, 0.8110p.u, 0.9346p.u, and 0.8393p.u and hence outside the steady acceptable voltage limits (i.e. 0.95 - 1.05p.u). These demonstrate that the system is on the verge of instability and may pilot to system collapse. As such, there is need for effective voltage control. Due to voltage instability from the results obtained in base case, the proposed DA is introduced to determine the optimal site and size of STATCOM device for voltage stability enhancement of the network.

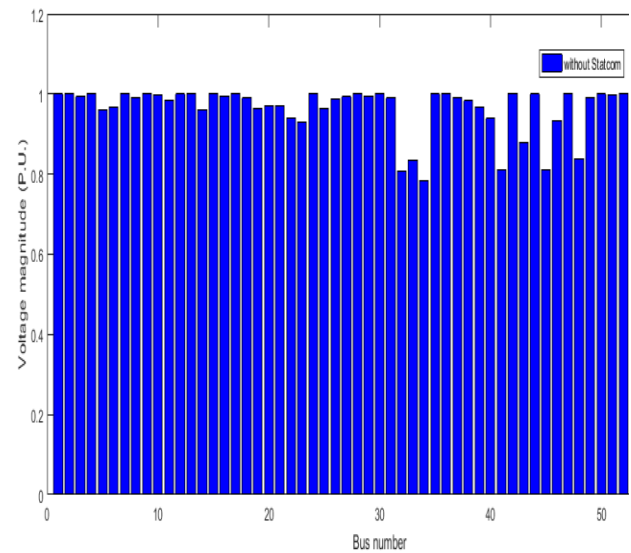


Fig.5. Voltage Profile without STATCOM

The power flow is performed in Five (5) cases with different number of STATCOMs namely; 2, 4, 6, 8, and 10 respectively.

The results of how the voltage profiles are controlled are achieved with 10 STATCOM devices and performance comparison is presented in this sub section. The STATCOMs are employed optimally into the network at buses 6 (Ikeja West), 18 (Alaoji), 22 (Makurdi), 23 (B/ Kebbi), 25 (Oshogbo), 34 (Maiduguri), 43 (Sakete), 45 (Jalingo), 48 (Kano) and 52 (AES). Consequently, the voltage profiles are controlled significantly, for the network to

operate stably within the specific voltage limit as shown in Figure 6.

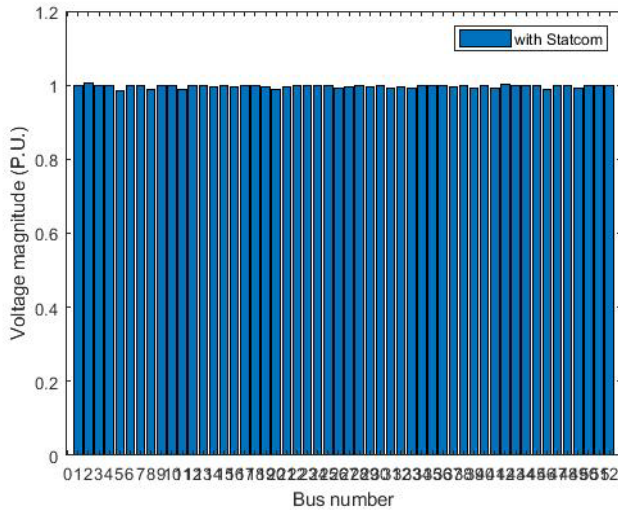


Fig.6. Voltage Profiles with STATCOM

The voltage profiles of buses outside the acceptable limits are considered as weak buses and are as shown separately in Fig. 7. It is noticed from the Figure that the voltage magnitudes of identified weak buses (22, 23, 32, 33, 34, 40, 41, 43, 45, 46, and 48) are improved from 0.9407 p.u., 0.9306 p.u., 0.8073 p.u., 0.8345 p.u., 0.7824 p.u., 0.9384 p.u., 0.8120 p.u., 0.8797 p.u., 0.8110 p.u., 0.9346 p.u., and 0.8393 p.u. to 1.0 p.u., 1.0 p.u., 0.9964 p.u., 0.9990 p.u., 0.9918 p.u., 1.0 p.u., 1.0 p.u., 1.0 p.u., 1.0 p.u., 0.9876 p.u., and 1.0 p.u. respectively.

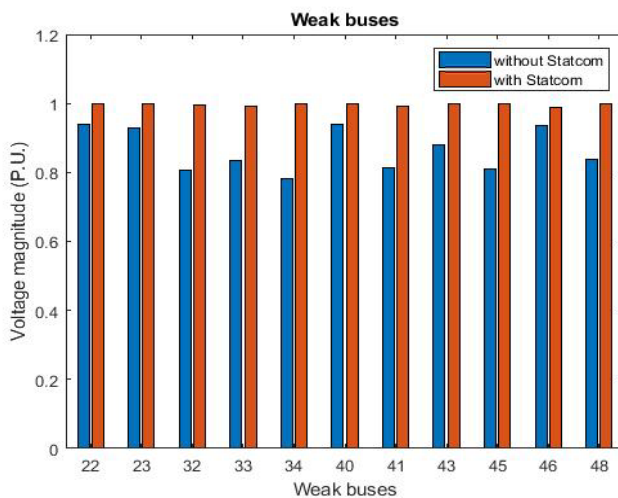


Fig.7. Voltage Profile of Weak Buses with and without STATCOM

Some other healthy buses (2, 3, 5, 6, 10, 11, 13, 14, 16, 18-21, 25-27, 29, 37-39, 42, 49 and 51) voltage profiles are also improved as a result of STATCOM placement as shown in Fig. 8.

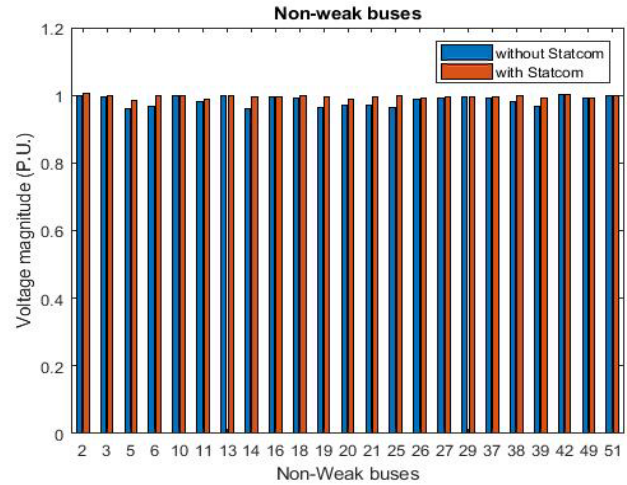


Fig.8. Voltage Profile of other Affected Buses

In comparison with and without STATCOM, the voltage profile of weak buses are enhanced significantly to 1.0 p.u., 1.0 p.u., 0.9964 p.u., 0.9990 p.u., 0.9918 p.u., 1.0 p.u., 1.0 p.u., 1.0 p.u., 1.0 p.u., 0.9876 p.u., and 1.0 p.u. respectively, as shown in Figure 9. Some other healthy buses voltage profiles are also increased upon the existing magnitudes. However, the worst voltage magnitude is realized at bus 34 (Maiduguri) with 0.7824 p.u. but later increased to 0.9918 p.u.

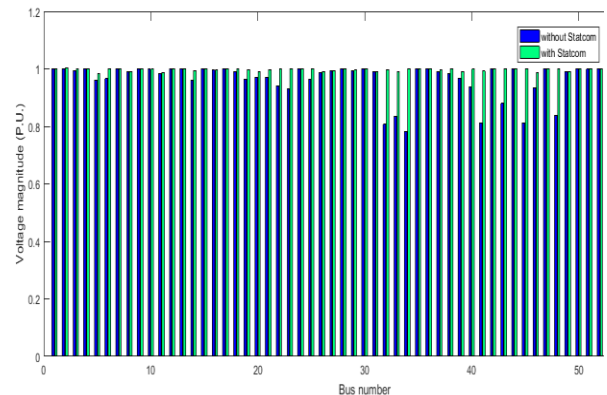


Fig.9. Comparison of Voltage Profile without and with STATCOMs

The comparison of VPEI as a result of optimal STATCOMs incorporation into the network using DA, for voltage stability enhancement is shown in Figure 10. It is observed from the Figure that with 2, 4, 6, and 8 numbers of STATCOMs, the VPEI are 1.0993, 1.1059, 1.1073 and 1.1115 respectively. But when 10 devices are employed, the VPEI is improved and found to be 1.1126.

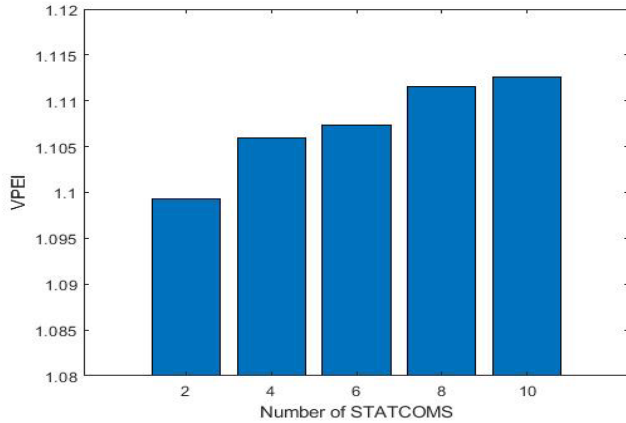


Fig.10. VPEI Representation for Diverse Number of STATCOMs

The summary of simulation results for the network is presented in Table 1. The table depicts how the DA technique employment resulted in the optimal allocation of

STATCOMs at dissimilar locations with different capacities, number of devices allocated, voltage profile index at both base and optimal cases, convergence characteristics and finally VPEI.

10. CONCLUSION

This paper has presented the application of DA algorithm for the optimal allocation of STATCOM device for voltage stability enhancement.

The simulation is carried out using Newton Raphson power flow technique, in MATLAB 2018a environment and on 52-Bus Nigerian transmission network. Ten (10) devices are optimally placed at buses 6 (Ikeja West), 18 (Alaoji), 22 (Makurdi), 23 (B/Kebbi), 25 (Oshogbo), 34 (Maiduguri), 43 (Sakete), 45 (Jalingo), 48 (Kano) and 52 (AES), with optimal sizes of 47.3 MVar. Convergence is achieved in 18 numbers of iterations after 50 distinct trials. The best result signifies enhancement in voltage stability of the network by 11.26% as compared to base case.

Table 1: Summary of Simulation Results with and without STATCOM Device for Diverse cases

Case	No. of STATCOM	Location (Bus)	Size (MVar)	Base case VPI	Optimal case VPI	VPEI
1	2	33,48	34.58	3.5931	3.9499	1.0993
2	4	41,43,48,52	29.96	3.5931	3.9736	1.1059
3	6	11,22,43,45,48,51	20.04	3.5931	3.9786	1.1073
4	8	23,31,33,34,39,40,43,48	19.67	3.5931	3.9937	1.1115
5	10	6,18,22,23,25,34,43,45,48,52	19.04	3.5931	3.9976	1.1126

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