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Original Research Article

Voltage Profile Enhancement on the Nigerian 330 kV Grid using Series-Shunt Reactive Power Compensation Technique

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ABSTRACT

The Nigerian 330 kV power systems is characterized by major constraints such as low voltage profile and power losses resulting in negative effects on power generation and transmission systems. This paper investigated the application of combining series and shunt compensations for enhancing the operation of the system. The load flow study using Newton-Raphson-based method was carried out to analyse the steady state operation of the system for the base case. This method converges faster and its simpler compared to other solution methods. The series compensation was incorporated, followed by the shunt compensation and then combined series and shunt compensation were incorporated into the system in sequential order. MATLAB/SIMULINK software was used to carry out the simulation analysis. The results obtained from the study revealed that the magnitude of bus voltages fall below the prescribed statutory range of 0.95<1.0<1.05 pu (that is ±5% of nominal voltage value). The combined series and shunt compensations method significantly increased power transfer and improved voltage profile of the overall Nigerian 330 kV grid network. It also showed that the operational behaviour and network performance of the Nigerian power system can be significantly improved.

1. INTRODUCTION

Electrical power is generally expected to be balanced so as to meet up with its increasing demand on the network in terms of real power as well as reactive power. This is an important factor for a secured operation of a power system for the sake of keeping the system frequency and voltage constant (Pappachen and Fathima, 2017; Alsokhiry and Adam, 2020). Most power networks, however, are being operated close to their thermal limits, which could be attributed to the continuous power demand increase (Bennett *et al.*, 2019). This usually results whenever a shortage in the reactive power in the system is experienced, which could lead to a serious instability and hence cascading failure (Choi and Song, 2020; Dui *et al.*, 2020; Zhang *et al.*, 2020). This is one of the problems facing weak networks such as the Nigerian grid system in recent times.

Instability and total blackout is frequently experienced in a weak network such as the Nigerian grid due to shortage of reactive power (Dada, 2014; Nnaji *et al.*, 2019). Hence, shortage of reactive power within a practical power network is a great issue to electric utilities and operators all over the world (Davidson *et al.*, 2000; Dilip and Gopal, 2017).To overcome this, and to maintain a secure and a stable operation, it is necessary to augment the reactive power in the system thereby controlling the voltage magnitudes and voltage angles and reducing the network losses. Furthermore power networks of today are large and complex due to interconnections of the network elements (Alexandridis and Papageorgiou, 2017; Ren *et al.*, 2020). Consequently, modern power systems are becoming more and more vulnerable as a result of large interconnections of network elements (Chaudhary and Rizwan, 2018). To adequately assess the system performance as well as its security status, the voltage stability limits must be maintained. For instance, the voltage magnitudes and voltage angles must be within the tolerance range, losses must be kept to the barest minimum, power transfer must be relatively high (Shaaban *et al.*, 2003; Kolcun *et al.*, 2016; Yang and Jiang, 2017; Chaudhary and Rizwan, 2018).

In any given power system network, to maintain a relatively constant frequency and voltage, there must be an equilibrium state between electric energy generation and electric power demands plus losses. The loss of equilibrium between the generation and the demand plus losses have caused lots of voltage collapse in many power systems in recent times. This total blackout could also be associated with a network whose transmission lines are overloaded, having very long radial transmission lines, or having inadequate generation capacity (Dada, 2014; Zhang *et al.*, 2019).

Traditionally, reinforcement of power transmission networks has usually been primarily through the construction of new transmission corridors, which involve construction or bringing in new substations and their associated equipment. The main challenge with this traditional-based approach, however, lies in the challenges faced in acquiring the right-of-way. Another problem with the approach is the high cost associated with the building of additional new infrastructures, which could also be time-consuming (Kishore and Singal, 2014; Hashemi and Zarif, 2019).

These challenges can easily be overcome through reactive power augmentation for the economic and optimal network operations (Liudvinavičius, 2017; Dash and Swain, 2018). Therefore, the aim of this work is to enhance the voltage profile and reduce the losses within the Nigerian grid system using combined shunt and series compensation techniques.

2. METHODOLOGY

2.1. Research Approach

A code was developed and simulated in the matlab environment using Matlab 17b, where base case was introduced into the code compensation which comprises shunt, series and combined where generated. The simulation results obtained as presented in Table 1 showed the base case solution to power flow problem using Newton-Raphson method, the results of the study showed that the magnitude of bus voltages at Jos, (bus 5), Kaduna (bus 6), Yola (bus 13), Gombe (bus 16), Damaturu (bus 19), Kano (bus 22), Oshogbo (bus 26), Ayede (bus 34), Maiduguri (bus 38) and Jalingo (bus 39) fell below(outside) the prescribed statutory range ($0.95 < 1.0 < 1.05$ p.u.) of nominal voltage values.

2.2. Mathematical Formulations

The analysis of transmission network involves proper modeling of the network such that the accuracy of the results is not compromised. One good method through which this could be realized is by considering the equivalent π-model technique for the transmission network. In general, this could be considered from the perspective of a simple two-port power network. In this research, this was used to derive the expressions for voltage and current phasors at both the sending-end and receiving-end, respectively, as a function of the network ABCD parameters.

Consider an equivalent network of a simple power system consisting of two buses (generator and load buses) connected by a transmission line shown in Figure 1.

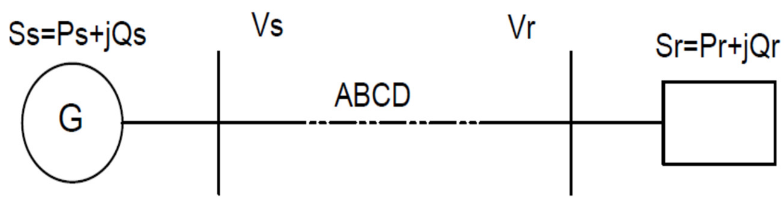

Figure 1: An equivalent network of a simple power network

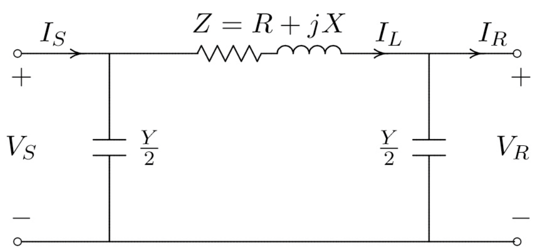

Figure 2: Equivalent π-form of a transmission network

The transmission line network of Figure 1 can easily be modelled using equivalent π-model technique to produce Figure 2. From Figure 1 the flow of both the real and reactive powers through the line considering a simple 2-bus system shown in Figure 2 can easily be derived in terms of the ABCD parameters as follows: The voltage phasor at the receiving-end can be expressed as:

$$V_r = |V_r| \angle 0^\circ \tag{1}$$

Similarly, the voltage phasor at the sending-end can be expressed as:

$$V_s = |V_s| \angle \delta \tag{2}$$

Where δ is the sending-end voltage angle, r is the receiving-end, s is the sending-end, and V is the voltage.

The complex power flowing out of the sending-end into the receiving-end can be written as:

$$\left.\begin{array}{l} S_s = P_s + jQ_s \\ S_s = V_s \times I_s^* \end{array}\right\} \tag{3}$$

Similarly, the complex power flowing into the receiving-end from the sending-end can be written as:

$$\left.\begin{aligned} S_r &= P_r + jQ_r \\ S_r &= V_r \times I_r^* \end{aligned}\right\} \tag{4}$$

where I_s^* and I_r^* are the complex conjugate of the sending- and receiving-end currents, S is complex power, P is real power, and Q is reactive power.

In terms of the network ABCD parameters, the sending- and receiving-end current expressions from Figure (2), are shown in Equations (5) and (6) respectively:

$$I_s = \frac{D}{B}V_s - \frac{V_r}{B} \tag{5}$$

$$I_r = \frac{V_s}{B} - \frac{AV_r}{B} \tag{6}$$

Where:

$$\left.\begin{aligned} A &= |A|\angle\alpha \\ B &= |B|\angle\beta \\ D &= A = |D|\angle\alpha \end{aligned}\right\} \tag{7}$$

By substituting Equation (5) into Equations (3) and (4), we have:

$$I_r = \frac{|V_s|}{|B|}\angle(\delta - \beta) - \frac{|A||V_r|}{|B|}\angle(\alpha - \beta) \tag{8}$$

$$I_s = \frac{|D||V_s|}{|B|}\angle(\alpha + \delta - \beta) - \frac{|V_r|}{|B|}\angle(-\beta) \tag{9}$$

Substituting the expressions in Equations (8) and (9) into Equations (3) and (4), yields:

$$S_r = \frac{|V_r||V_s|}{|B|}\angle(\beta - \delta) - \frac{|A||V_r|^2}{|B|}\angle(\beta - \alpha) \tag{10}$$

$$S_s = \frac{|D||V_s|^2}{|B|}\angle(\beta - \alpha) - \frac{|V_s||V_r|}{|B|}\angle(\beta + \delta) \tag{11}$$

Separation of the Equations (10) and (11) into their respective real and reactive power components yields:

$$P_r = \frac{|V_r||V_s|}{|B|}\cos(\beta - \delta) - \frac{|A||V_r|^2}{|B|}\cos(\beta - \alpha) \tag{12}$$

$$Q_r = \frac{|V_r||V_s|}{|B|}\sin(\beta - \delta) - \frac{|A||V_r|^2}{|B|}\sin(\beta - \alpha) \tag{13}$$

$$P_s = \frac{|D||V_s|^2}{|B|}\cos(\beta - \alpha) - \frac{|V_s||V_r|}{|B|}\cos(\beta + \delta) \tag{14}$$

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$$Q_s = \frac{|D||V_s|^2}{|B|}\sin(\beta - \alpha) - \frac{|V_s||V_r|}{|B|}\sin(\beta + \delta) \tag{15}$$

Generally, the resistance of a transmission line is practically insignificant compared with its reactance whose ABCD parameters are defined by:

$$\left.\begin{array}{l} A = 1\angle 0° \\ D = 1\angle 0° \\ B = |Z|\angle\theta \end{array}\right\} \tag{16a}$$

$$\left.\begin{array}{l} A = 1\angle 0° \\ D = 1\angle 0° \\ B = |X|\angle 90° \end{array}\right\} \tag{16b}$$

Equations (12) and (13) can, therefore, be modified as:

$$P_r = \frac{|V_r||V_s|}{|X|}\sin\delta \tag{17}$$

$$Q_r = \frac{|V_r||V_s|}{|X|}\cos\delta - \frac{|V_r|^2}{|X|} \tag{18}$$

2.3. Modelling of Capacitor using Newton-Raphson Iterative Method

The Newton-Raphson method generally involves finding a solution to n nonlinear algebraic Equations in n unknowns, which can be expressed as

$$f_i(x_1, x_2, ..., x_n) = 0 \tag{19a}$$

where $i = 1,2,3,...,n$

Initial estimate of the n unknowns given by $x_1^0, x_2^0, ..., x_n^0$ are usually required for the solution, of the n nonlinear algebraic Equations, to be obtained using Newton-Raphson iterative method. Therefore, let the small deviation from the true values, which on being added to the initial values to give the actual solution be $\nabla x_1^0, \nabla x_2^0, ..., \nabla x_n^0$.

Consequently,

$$f_i\left(x_1^0 + \nabla x_1^0, x_2^0 + \nabla x_2^0, ..., x_n^0 + \nabla x_n^0\right) = 0 \tag{19b}$$

By applying Taylor's series to the left hand side of Equation (19a), gives:

$$f_i^0\left(x_1^0, ..., x_n^0\right) + \left[\left(\frac{\partial f_i}{\partial x_1}\right)^0 \nabla x_1^0 + ... + \left(\frac{\partial f_i}{\partial x_n}\right)^0 \nabla x_n^0\right] + \text{higher-order terms} = 0$$

where $\left(\frac{\partial f_i}{\partial x_1}\right)^0,...,\left(\frac{\partial f_i}{\partial x_n}\right)^0$ are the derivatives of f_i with reference to $x_1, x_2,..., x_n$ estimated around $x_1^0, x_2^0,..., x_n^0$.

If the errors $\nabla x_1^0, \nabla x_2^0,..., \nabla x_n^0$ in Equation (19b) are assumed to be very small, the higher-order terms are therefore negligibly and the resulting Equation becomes:

$$f_i^0\left(x_1^0,...,x_n^0\right)+\left[\left(\frac{\partial f_i}{\partial x_1}\right)^0 \nabla x_1^0 + ... + \left(\frac{\partial f_i}{\partial x_n}\right)^0 \nabla x_n^0\right] \approx 0 \quad (20a)$$

In matrix form, Equation (20a) can be written as:

$$\begin{bmatrix} f_1 \\ . \\ . \\ . \\ f_n \end{bmatrix} + \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1}\right)^0 & . \; . \; . & \left(\frac{\partial f_1}{\partial x_n}\right)^0 \\ . & . \; . \; . & . \\ . & . \; . \; . & . \\ . & . \; . \; . & . \\ \left(\frac{\partial f_n}{\partial x_1}\right)^0 & . \; . \; . & \left(\frac{\partial f_n}{\partial x_n}\right)^0 \end{bmatrix} \times \begin{bmatrix} \nabla x_1^0 \\ . \\ . \\ . \\ \nabla x_n^0 \end{bmatrix} \approx 0 \quad (20b)$$

Vectorially, Equation (20b) can be presented as:

$$f^0 + J^0 \times \nabla x^0 = 0 \quad (21)$$

where J is the Jacobian matrix evaluated around x^0.

Solution of Equation (21) gives the estimated values of $\nabla x_1^0, \nabla x_2^0,..., \nabla x_n^0$, which are used to update the solution to get the first iterative solution as:

$$\left.\begin{matrix} x_1^1 = x_1^0 + \nabla x_1^0 \\ . \\ . \\ . \\ x_n^1 = x_n^0 + \nabla x_n^0 \end{matrix}\right\} \quad (22)$$

Generally, the $(p+1)th$ iteration values are:

$$x_i^{p+1} = x_i^p + \nabla x_i^p, \quad \text{for } i = 1,2..., n \quad (23)$$

The iterations are then repeated till Equation (19a) is satisfied to the desired accuracy. That is, the process is repeated until the value of the correction vector $\nabla x_1^p, \nabla x_2^p,..., \nabla x_n^p$ is less than the prescribed value.

2.4. Formulation of Power-Flow Problems

From the fundamental circuit theory perspectives, the total complex power injection at bus i in an $n-bus$ -bus power network is given by

$$S_i = V_i I_i^* \qquad \text{for } i = 1, 2, \ldots, n \tag{24}$$

$$S_i^* = V_i^* I_i = P_i - jQ_i, \qquad \text{for } i = 1, 2, \ldots, n \tag{25}$$

At the bus i:

$$I_i = \left[\sum_{j=1}^{n} Y_{ij} V_j \right] \tag{26}$$

Therefore, Equation (25) becomes:

$$P_i - Q_i = V_i^* \left[\sum_{j=1}^{n} Y_{ik} V_k \right] \tag{27}$$

Separating the RHS of Equation (27) into its real and reactive components, gives:

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) \tag{28}$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \tag{29}$$

Where $V_i = |V_i| \angle \delta_i$,

$V_k = |V_k| \angle \delta_k$

$Y_{ik} = |Y_{ik}| \angle \theta_{ik}$

Using Newton-Raphson method, the sets of nonlinear algebraic equations presented in Equations (30) and (31) can be rearranged as (Kulworawanichpong, 2010; Gatilov, 2014)

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_4 & J_3 \end{bmatrix} \begin{bmatrix} \Delta \delta_i \\ \Delta V_i \end{bmatrix} \tag{30}$$

Where:

$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix}$ represents the column vector of power mismatches at both load and generator buses.

$\begin{bmatrix} \Delta \delta_i \\ \Delta V_i \end{bmatrix}$ represents the column vector of the unknown variables at both load and generator buses.

The square matrix of Equation (30) is known as the Jacobian matrix whose elements are J_1, J_2, J_3 and J_4. These Jacobian elements are defined as follows:

$$J_{1,ik} = \frac{\partial P_i}{\partial \delta_k} \tag{31}$$

$$J_{1,ii} = \frac{\partial P_i}{\partial \delta_i} \tag{32}$$

$$J_{2,ik} = \frac{\partial P_i}{\partial |V_k|} \tag{33}$$

$$J_{2,ii} = \frac{\partial P_i}{\partial |V_i|} \tag{34}$$

$$J_{3,ik} = \frac{\partial Q_i}{\partial \delta_k} \tag{35}$$

$$J_{3,ii} = \frac{\partial Q_i}{\partial \delta_i} \tag{36}$$

$$J_{4,ik} = \frac{\partial Q_i}{\partial |V_k|} \tag{37}$$

$$J_{4,ii} = \frac{\partial Q_i}{\partial |V_i|} \tag{38}$$

Application of triangular factorization to Equation (30) helps in determining the values of the unknown vectors $\Delta\delta_i$ and ΔV_i.

Updating these calculated values of voltage magnitudes and voltage angles, yields:

$$\delta_i^p = \delta_i^p + \Delta\delta_i^p \tag{39}$$

$$V_i^p = V_i^p + \Delta V_i^p \tag{40}$$

where p is the required number of iterations. The iteration number p is achieved when the conditions of Equation (41) imposed on the mismatch real and reactive powers are satisfied:

$$\left.\begin{array}{l} \nabla P \leq \varepsilon \\ \nabla Q \leq \varepsilon \end{array}\right\} \tag{41}$$

where ε is a small prescribed value, whose value is 0.0001 in this study.

The voltage magnitudes obtained that is outside the statutory limits $(V_{\min} < V_i < V_{\max})$ of $\pm$ 5% of nominal value or $(0.95 < V_i < 1.05)$ is identified. The bus associated with these identified voltage values are the suitable buses where the reactive power needs to be injected.

To determine the power loss through the transmission lines, the complex power flow through the lines $i-k$ is considered as:

$$S_{ik} = V_i I_{ik}^* = P_{ik} + jQ_{ik} \quad (42a)$$

$$S_{ik} = V_i \left(V_i^* - V_k^*\right) y_{ik}^* + V_i V_k^* \; y_{iko}^* \quad (42b)$$

The complex power flow through the lines $k-i$ can as well be expressed as:

$$S_{ki} = V_k I_{ki}^* = P_{ki} + j Q_{ki} \quad (43a)$$

$$S_{ki} = V_k \left(V_k^* - V_i^*\right) y_{ki}^* + V_k \; V_i^* \; y_{kio}^* \quad (43b)$$

Total real and reactive power losses can therefore be expressed in Equations (44) and (45) respectively:

$$P_{ik} + P_{ki} = \Re\left\{S_{ik}\right\} + \Re\left\{S_{ki}\right\} \quad (44)$$

$$Q_{ik} + Q_{ki} = \Im\left\{S_{ik}\right\} + \Im\left\{S_{ki}\right\} \quad (45)$$

The simulations were carried out in order to study the steady state power flow analysis on the Nigerian 330 kV 40-bus network as shown in Figure 3. The base case steady state power flow solution when carried out provided the voltages at various points in the system as well as the power losses real and reactive powers. The same simulation is repeated when series, shunt and series-shunt compensators were incorporated into the system and the results of the simulations were obtained.

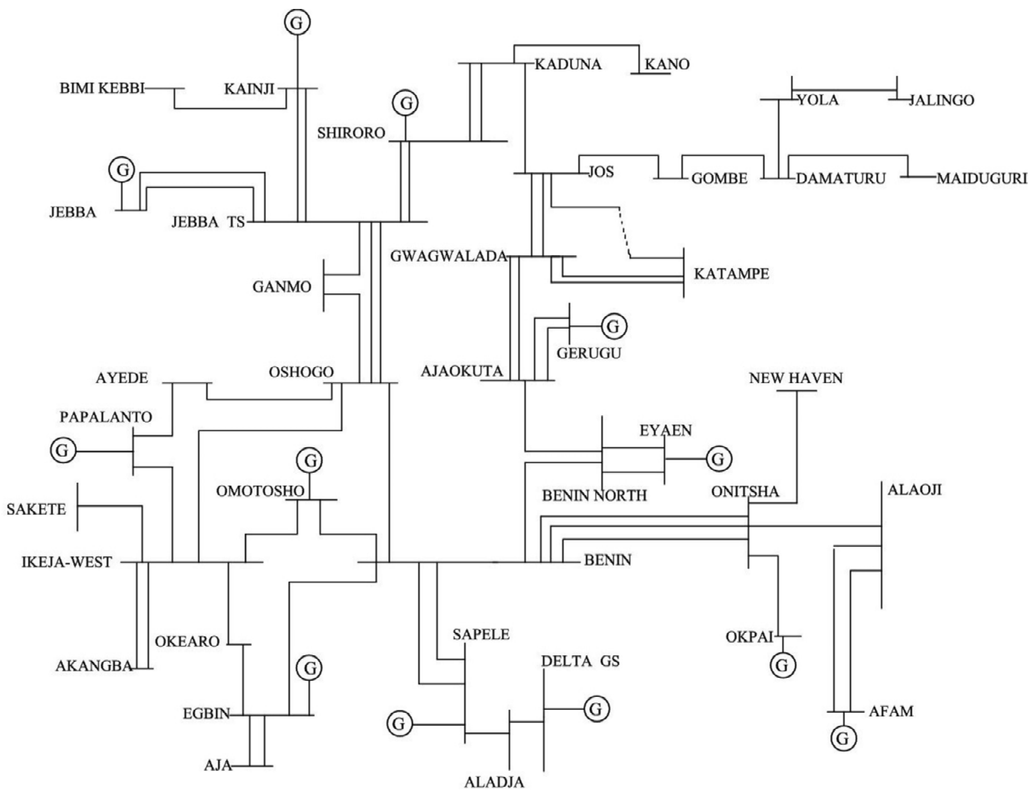

Figure 3: Single-line diagram of the Nigerian 330-kV 40-bus network (Ogbuefi and Madueme, 2015)

3. RESULTS AND DISCUSSION

The result of the base case power flow solution based on Newton-Raphson iterative technique is in column three of Table 1. From these results, it can be seen that voltage magnitude at Jos, (bus 5), Kaduna (bus 6), Yola (bus 13), Gombe (bus 16), Damaturu (bus 19), Kano (bus 22), Oshogbo (bus 26), Ayede (bus 34), Maiduguri (bus 38) and Jalingo (bus 39) fell below(outside) the prescribed statutory range (0.95 $< 1.0 <$ 1.05 p.u.) of nominal voltage values. The poor voltage profile identified at some of the buses within the Nigerian 330-kV network as presented in Table 1, therefore needs to be improved for efficient operation of the network. This enhancement was carried out by investigating the influence of shunt compensation, series compensation and then an combined compensation on the voltage profile of the network. The real and reactive power losses for the base case solution are 222 MW and 1662 MVAR respectively as presented in Table 2.

Table 1: Voltage magnitudes obtained for series, shunt and combined compensations

Node No.	Node name	Base case voltage (per unit)	Compensation voltage magnitude (per unit)		
			Shunt	Series	Combined
1	Egbin	1.000	1.000	1.000	1.000
2	Kainji	1.000	1.000	1.000	1.000
3	Jebba	1.000	1.000	1.000	1.000
4	Akangba	0.973	0.975	0.976	0.980
5	Jos	**0.925**	**1.037**	**0.952**	**1.045**
6	Kaduna	**0.945**	**0.998**	**0.957**	**1.002**
7	Ikeja	0.977	0.980	0.981	0.984
8	Shiroro	1.000	1.000	1.000	1.000
9	Benin	0.990	0.992	0.999	1.002
10	Aladja	0.998	0.998	0.998	0.998
11	Onitsha	0.984	0.985	0.987	0.988
12	Afam	1.000	1.000	1.000	1.000
13	Yola	**0.875**	**1.039**	**0.928**	**1.041**
14	Gerugu	1.000	1.000	1.000	1.000
15	BirniKebbi	0.966	0.966	0.966	0.966
16	Gombe	**0.879**	**1.038**	**0.925**	**1.043**
17	Sapele	1.000	1.000	1.000	1.000
18	Ajaokuta	1.002	1.002	1.003	1.000
19	Damaturu	**0.856**	**1.001**	**0.902**	**1.022**
20	New Haven	0.966	0.966	0.969	0.969
21	Alaoji	1.000	1.000	1.000	1.000
22	Kano	**0.817**	**0.970**	**0.912**	**0.982**
23	Sakete	0.962	0.964	0.965	0.969
24	Okpai	1.000	1.000	1.000	1.000
25	Katampe	0.975	0.975	0.975	0.975
26	Oshogbo	**0.931**	**0.978**	**0.953**	**0.978**
27	Jebba TS	0.997	0.999	1.000	1.002
28	Aja	0.996	0.996	0.996	0.996
29	Papalanto	1.000	1.000	1.000	1.000
30	Omotosho	1.000	1.000	1.000	1.000
31	Delta GS	1.000	1.000	1.000	1.000
32	Ganmo	0.962	0.985	0.974	0.986
33	Okearo	0.988	0.988	0.989	0.986

Node No.	Node name	Base case voltage (per unit)	Compensation voltage magnitude (per unit)		
			Shunt	Series	Combined
34	Ayede	**0.857**	**0.990**	**0.898**	**0.999**
35	P/Harcourt	0.997	0.997	0.997	0.997
36	Eyaen	1.000	1.000	1.000	1.000
37	Benin North	0.999	0.999	0.999	1.000
38	Maiduguri	**0.847**	**1.015**	**0.894**	**1.028**
39	Jalingo	**0.869**	**1.037**	**0.924**	**1.041**
40	Gwagwalada	0.977	0.977	0.977	0.977

Table 2: Results of comparison compensation techniques

Compensation	Active loss	Reactive loss
Base case	222 MW	1662 MVAR
Series compensation	222 MW	971 MVAR
Shunt compensation	202 MW	1510 MVAR
Combined compensation	215 MW	937 MVAR

When all the three compensations were applied, one after the other, the active power loss and reactive power loss obtained amounted to 215 MW and 937 MVAR respectively. The results provided are presented in Table 2. It was shown that the application of a shunt compensation method provides a significant decrease in the network losses as well as increase in the transmission network performance compared to series compensation method. With these benefits of shunt compensation, however, the simultaneous application of the combined compensation, which is the combination of both the series and shunt compensations, provided an enhanced transfer of power, improved voltage magnitudes and angles, as well as better transmission performance when applied on the Nigerian grid network. The implication of this is that the combined compensation presents the benefits of both the series and shunt compensation methods when applied.

4. CONCLUSION

The effects of shunt, series, and hybrid or combined compensations on line losses, power transfer capability, voltage profile and efficiency in a practical power system have been investigated in this work. The study uses Nigerian 330 kV, 40-bus transmission grid system as a case study. Relevant mathematical formulations are presented. The results obtained from the study show that series compensation has a greater advantage in increasing the power transfer within the network while shunt compensation helps in improving voltage profile of the network and thus enhancing the overall efficiency of the system. It has been shown that the use of combine compensation method technique gives a better improvement in the network operation in terms of power transfer, reduction in network losses, voltage profile enhancement as well as improved transmission performance in a power system. Based on the foregoing, it can be concluded that the combined compensation is more profitable to be explored in enhancing the operation of a weak practical power system such as Nigerian 330 kV power system. The approach can, therefore, serve as an alternative, to the use of FACTS, which is more expensive. It is also an alternative, which is more economical compared to the installation of new substation and construction of new lines.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Błachut, J. and Jaiswal, O.R. (1998a). Buckling under external pressure of closed toroids with circular and elliptical Alexandridis, A. T. and Papageorgiou, P. C. (2017). A complex network deployment suitable for modern power distribution analysis at the primary control level. *IFAC-PapersOnLine*, *50*(1), pp. 9186–9191.

Alsokhiry, F. and Adam, G. P. (2020). Electrical Power and Energy Systems Limitations of voltage source converter in weak ac networks from voltage stability point of view. *Electrical Power and Energy Systems*, 119, p. 105899.

Bennett, J. A., Fuhrman, J., Brown, T., Andrews, N., Fittro, R. and Clarens, A. F. (2019). Feasibility of Using sCO_2 Turbines to Balance Load in Power Grids with a High Deployment of Solar Generation. *Energy*, *181*, pp. 548–560.

Chaudhary, P. and Rizwan, M. (2018). Voltage regulation mitigation techniques in distribution system with high PV penetration: A review. *Renewable and Sustainable Energy Reviews*, *82*, pp. 3279–3287.

Choi, E. and Song, J. (2020). International Journal of Disaster Risk Reduction Cost-effective retrofits of power grids based on critical cascading failure scenarios identified by multi-group non-dominated sorting genetic algorithm. *International Journal of Disaster Risk Reduction*, *49,* p. 101640.

Dada, J. O. (2014). Towards understanding the benefits and challenges of Smart/Micro-Grid for electricity supply system in Nigeria. *Renewable and Sustainable Energy Reviews*, *38*, pp. 1003–1014.

Dash, R. and Swain, S. C. (2018). Effective Power quality improvement using Dynamic Activate compensation system with Renewable grid interfaced sources. *Ain Shams Engineering Journal*, *9*(4), pp. 2897–2905.

Davidson, I. E., Okafor, F. N., Jimoh, A. A. and Ojo, J. O. (2000). Power System Control Automation in Developing Economies - The Nigerian Experience. *IFAC Proceedings Volumes*, *33*(18), pp. 93–97.

Dilip, M. and Gopal, S. (2017). *A Review on Reactive Power Compensation Technologies. International Journal of Innovative Technology and Exploring Engineering*, *4*(11), pp. 249–253.

Dui, H., Meng, X., Xiao, H. and Guo, J. (2020). Analysis of the cascading failure for scale-free networks based on a multi- strategy evolutionary game. *Reliability Engineering and System Safety*, *199*, p. 106919.

Gatilov, S.Y. (2014). Using low-rank approximation of the Jacobian matrix in the Newton – Raphson method to solve certain singular equations. *Journal of Computational and Applied Mathematics*, *272*, pp. 8–24.

Hashemi, M. and Zarif, M. H. (2019). A novel hierarchical distributed framework for optimal reactive power dispatch based on a system of systems structure. *Computers and Electrical Engineering*, *78*, pp. 162–183.

Kishore, T. S. and Singal, S. K. (2014). Optimal economic planning of power transmission lines: A review. *Renewable and Sustainable Energy Reviews*, *39*, pp. 949–974.

Kolcun, M., Čonka, Z., Beňa, L., Kanálik, M. and Medveď, D. (2016). Improvement of Transmission Capacity by FACTS devices in Central East Europe power system. *IFAC-PapersOnLine*, *49*(27), pp. 376–381.

Kulworawanichpong, T. (2010). Simplified Newton – Raphson power-flow solution method. *International Journal of Electrical Power and Energy Systems*, *32*(6), pp. 551–558.

Liudvinavičius, L. (2017). Compensation of Reactive Power of AC Catenary System. *Procedia Engineering*, *187*, pp. 185–197.

Nnaji, E. C., Adgidzi, D., Dioha, M. O., Ewim, D. R. E. and Huan, Z. (2019). Modelling and management of smart microgrid for rural electrification in sub-saharan Africa: The case of Nigeria. *Electricity Journal*, *32*(10), p. 106672

Ogbuefi, U. C. and Madueme, T. C. (2015). A Power Flow Analysis of the Nigerian 330 kV Electric Power System. A Power Flow Analysis of the Nigerian 330 KV Electric Power System. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, *10*(1), pp. 46–57.

Pappachen, A. and Fathima, A. P. (2017). Critical research areas on load frequency control issues in a deregulated power system: A state-of-the-art-of-review. *Renewable and Sustainable Energy Reviews*, *72*, pp. 163–177.

Ren, H. P., Gao, Y., Huo, L., Song, J. H. and Grebogi, C. (2020). Frequency stability in modern power network from complex network viewpoint. *Physica A: Statistical Mechanics and Its Applications*, *545*, p. 123558.

Shaaban, M., Li, W., Yan, Z., Ni, Y. and Wu, F. F. (2003). Calculation of total transfer capability incorporating the effect of reactive power. *Electric Power Systems Research*, *64*(3), pp. 181–188.

Yang, J. and Jiang, K. (2017). The sensitive line identification in resilient power system based on fault chain model. *International Journal of Electrical Power and Energy Systems*, *92*, pp. 212–220.

Zhang, C., Xu, X. and Dui, H. (2020). Analysis of network cascading failure based on the cluster aggregation in cyber-physical systems. *Reliability Engineering and System Safety*, *202*, p. 106963.

Zhang, H., Cheng, H., Liu, L., Zhang, S., Zhou, Q. and Jiang, L. (2019). Coordination of generation, transmission and reactive power sources expansion planning with high penetration of wind power. *International Journal of Electrical Power and Energy Systems*, *108*, pp. 191–203.