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FORTIFICATION OF THE 330-KV NIGERIAN NETWORK USING RENEWABLE ENERGY RESOURCES

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ABSTRACT

This work studies the impact of renewable energy source (RES) on the optimal power flow (OPF) solution of the Nigerian 330-kV power system network. In a previous OPF analysis of the Nigerian power system network, which was carried out with the inclusion of flexible alternating current transmission system (FACTS) devices, the results presented showed that voltage magnitudes of some buses were outside the tolerable limits and so static synchronous compensator (STATCOM) was applied to improve the voltage magnitude profile of the network. However, since such locations with intolerable limits have been reported to have good renewable energy potentials, it becomes necessary to study the effect of utilising RES in place of STATCOM. 50 MW out of the reported renewable energy potentials of the locations is used for this study. The results obtained show that though, there exist some similarities in the inclusion of STATCOM and RES in the OPF analysis, yet the inclusion of RES optimally readjusted the real power distribution in the system, thereby reducing the hourly fuel cost by 9.23% as compared to 1.2% recorded for the case of STATCOM.

Keywords: *Optimal Power Flow, Renewable Energy, Nigerian Network, MATLAB.*

INTRODUCTION

Due to the large geographical spanning of existing power systems (PS), some remote load centers have to depend on energy generated into the grid from far large power plants. Most of these large power plants are either fossil fuel based or hydro based. However, if these remote locations have good renewable energy potential, it is necessary to harness this potential to reduce their over dependence on the far-flung power plants and further reducing the cost of fuel used by the thermal plants. Examples of RES that can be harnessed are hydro, solar, wind, geothermal etc (Aliyu *et al.*, 2015).

Hydro power generation involves the conversion of water energy into electrical energy with the assistance of hydraulic turbinesand electric generators. A major advantage of the hydro power plant (HPP) is its quick starting ability, which makes it possible for the plant to be able to connect to load within few minutes. This ability of the HPP allows it to respond to rapidly changingloads without loss of efficiency (Brockschink *et al.*, 2001). This advantage has made most countries worldwide to consider HPP as a major source for meeting their electricity demand. Due to global interest in HPP, the world hydropower capacity in 2004 was 2810 TWh and is projected to be 4903 TWh by the year 2030, with 1.8% growth rate per year, nonetheless, the share will remain at 2% of the world energy supply (Bada, 2011). Though, just like most other RES, its initial capital investment is huge.

Solar power is the largest source of energy available today and it is derived from the sun. The energy from the sun is practically not exhaustible and as a result, it far exceeds any foreseeable future need (Lund, 2010).One way of harnessing this energy is through the use of photovoltaic (PV) solar cells which are used to convert the energy from sunlight into electrical energy. To achieve a substantial amount of electrical energy, many PV cells are connected in series, parallel or a combination of the two to form a panel (Liang and Liao, 2007; Lund, 2010). Apart from the production of electricity through PV solar panels, solarcollectors are also used to concentrate the heat from the sun to generate steam which could be used to drive a turbine inorder to generate electrical energy (Fardo and Patrick, 2009). This is usually referred to as concentrated solar-thermal power (CSP) (Cossent *et al.,* 2011).

Wind power plants (WPP) are designed and constructed to convert wind energy into electrical energy by the rotation of a blade-driven electric generator whenever there is adequate wind speed in the atmosphere (Lund, 2010). Since wind is a free and clean energy source, it has been considered as a source of energy for several years now.The first usage of wind for electricity generation was in Denmark in 1890 (Johnson, 2001). Since then, wind power has developed from the generation of few kilo-watts to few mega-watts of electrical energy (Lund, 2010). Today, large WPPs are competing with other forms of energy sources in supplying economical and clean power in many parts of the world (Patel, 1999). However, wind turbines (WT) are also used to rotate smallgenerators which could, potentially, be located at home. Although, solar and wind power systems are intermittent in nature, they are free and environmentally friendly. The problem caused by the intermittent nature of RES could be solved by effective weather forecasting and the introduction of energy storage systems like batteries (Liang and Liao, 2007).

Geothermal systems utilise the heat of molten masses below theearth. The principle of geothermal systems is similar to other steam turbinedriven systems. However, in this case, thesource of steam is the heat obtained from within the earth through wells that are drilled to a depth of two or more miles into the earth.One hole may be used to send cold waterdown into the very hot material located under the surface oftheearth. An adjacently drilled hole could be used to bring steam back tothe surface. This steam can be used to drive a steam turbine connected to a generator to produce electrical energy (Fardo and Patrick, 2009).

RES can be connected both at the transmission and distribution point in the grid. The voltage level at connection point of RES mainly depends on the renewable generation technology and the power capacity of the plant. It has been reported that renewable energy technologies such as CSP, wind power, mini (≤ 10 MW) and medium (> 10 MW and ≤ 50 MW) and hydro power can be injected into the grid at the transmission level (145-400 kV) (Cossent *et al.*, 2011). The voltage at the connection point is maintained at a normal level by the presence of adequate reactive support. It is important to note that the medium HPP uses synchronous generator and therefore, the reactive power is from the generators excitation system. Early WPPs also used synchronous generator.But forreasons bothering on economy and reliability, many grid connected wind power systems now use inductionmachines as the electrical generator (Johnson, 2001). Henceforth, the induction machine needs reactive power for excitation, the machine is either self-excited by shunt capacitors or externally excited from the grid network. However, if the induction machine is excited by the grid network, the grid network must be capable of supplying the required reactive power (Patel, 1999).

According to (Oseni, 2011), Nigerian power sector is reported to be underperforming. Hence,there is an urgent need for proper policy towards achieving a quality and continuous well-functioning electricity market in the country . One of such policy should focus on harvesting the enormous RES in the country. Examples of such RES are hydro, solar, wind and biomass. The solar radiation in the country ranges from 4 kWh/m^2 in the south to 7 kWh/m^2 in the north, which is sufficiently above the required threshold average value (of 2.3 kWh/m^2) for rural electrification (Mohammed *et al.*, 2013). A research on the wind power potentials for a number of Nigerian cities reveals that the annual wind speed ranges from 2.32 m/s for PortHarcourt to 3.89 m/s for Sokoto and the maximum extractable power perunit areafor these two cities was estimated as 4.51 and 21.97 wattsper square metre of blade area, respectively (Ajao *et al.*, 2009). According to Mohammed *et al.* (2013), unexploited hydropower potential of about 12,954.2 MW also exists.

Despite these endowments of RES, only the hydroelectric power source is being significantlyutilised, and its exploitation is even below its full potential while the solar power is used majorly amongurban households, and in some selected rural centres (Olatomiwa *et al.*, 2015). The major constraints in harnessing these huge RES potentials in the country are high initial cost, lack of appropriate policy, regulatory and institutional framework to stimulate demand and attract investors. Therefore, if the country will harvest these enormous potential of its RES on its drive to meet the ever increasing electricity demand, these constraints must be eradicated through significant investment in critical areas of research and development, building of indigenous human and manufacturing capacities and the intensification of the on-going economic reform to create an investor friendly environment (Sambo, 2008).

There are definitely some benefits from harnessing of RES for power systems operation. Top of these benefits, is the reduction in the total cost of fuel used for thermal plants generation (Liang and Liao, 2007). However, for an effective dispatch of generation in power systems, OPF analysis is a suitable mathematical tool. It involves the minimisation or maximisation of one or more objective function such that systems constraints are not violated. Examples of such objective functions are cost of generation, emission due to generation at thermal stations, transmission losses, customers' welfare etc. (Zhang *et al.*, 2006). The systems constraints that needs to be satisfied are power balance, voltage magnitude, real and reactive power, power flow on transmission lines etc. In the previous work of (Komolafe and Lawal, 2015), the OPF analysis of the Nigerian network was carried out with thermal plants fuel cost as objective function. In the said work, the voltage magnitude of some buses was discovered to be outside the tolerable limits. These buses are all in the Northern part of the country. These limits violation are as a result of the distances of these buses to power generating buses and the loads at those buses. Though, Static Synchronous Compensator (STATCOM) which is a reactive power source was used to effectively bring the voltage magnitude of the affected buses within limits. The locations of the buses where STATCOM are placed are Kano, Damaturu and Yola. Investigations have shown that these locations have promising RES potentials (Emodi and Boo, 2015; Ohunakin *et al.*, 2014; Shaaban and Petinrin, 2011).

Kano has been reported to have a combined small hydro power potential of 46.2 MW from various locations (Emodi and Boo, 2015; Mohammed *et al.*, 2013; Shaaban and Petinrin, 2011). Kano has also shown an all-time high wind power potential throughout the year (Mohammed *et al.*, 2013). A recent research showed that Kano has an estimated wind power potential of 917 MW and a good solar radiation which can be utilised for either PV or CSP system (Aliyu *et al.*, 2015). But as stated earlier, CSP as against the solar PV cell is better considered for transmission level (Cossent *et al.*, 2011).

Damaturu is situated in Yobe State, Nigeria. It has been shown that Yobe has an estimated wind power potential of 2244 MW (Emodi and Boo, 2015; Shaaban and Petinrin, 2011). This location also has good solar radiation which can be used for CSP (Emodi and Boo, 2015; Ohunakin *et al.*, 2014).

A study carried out by the energy commission of Nigeria (ECN) revealedthat total exploitable wind energy reserve at 10 m height for Yola is 8 MWh/yr (as cited in Emodi and Boo, 2015; Shaaban and Petinrin, 2011). Research has also shown that Yola has an exploitable hydropower of 360 MW from River Benue (as cited in Mohammed *et al.*, 2013). A detailed review of the RES potential of Nigeria can be found in (Mohammed *et al.*, 2013).

Due to the potentials of these three locations, the STATCOMs incorporated in the previous work of (Komolafe and Lawal, 2015) are therefore replaced by small capacity RES plants. This is with a view to studying the impact of RES in the OPF analysis of the Nigerian power network as against the inclusion of STATCOM.

OPTIMAL POWER FLOW PROBLEM DEFINITION

The optimal power flow as formulated in this work is as follows (Sun *et al.*, 1984; Acha *et al.*, 2004);

$$\text{Minimise} \quad F_T = \sum_{i=1}^{ng} (a_i + b_i P_i + c_i P_i^2) \qquad (1)$$

subject to the following power balance constraints:

$$P_k + P_{dk} - P_{gk} = 0 \tag{2a}$$

$$Q_k + Q_{dk} - Q_{gk} = 0 \tag{2b}$$

and inequality constraints

$$\left.\begin{array}{l} P_i^{\min} \le P_i \le P_i^{\max} \\ Q_i^{\min} \le Q_i \le Q_i^{\max} \\ V^{\min} \le V \le V^{\max} \end{array}\right\rangle \tag{3}$$

Where: F_T is the total cost of fuel for all thermal generating plants in the system.a_i, $b_i$and c_i are the cost coefficients of thermal station i.P_i and Q_i are, respectively, the active and reactive power generation at thermal station i.superscript *min* and *max*, respectively, represent minimum and maximum limits on variables. P_{dk} and Q_{dk} are, respectively, the active and reactive demand at bus k. P_{gk} and Q_{gk} are, respectively, the active and reactive power generation at bus k. it should be noted that if thermal station i is connected to bus k, $P_{gk} = P_i$ and $Q_{gk} = Q_i$.P_k and Q_k are, respectively, the real and the reactive power flow equations at bus k and are given as:

$$P_k = V_k \sum_{j=1}^{N} V_j Y_{jk} \cos(\delta_j - \delta_k + \theta_{jk}) \tag{4}$$

$$Q_k = -V_k \sum_{j=1}^{N} V_j Y_{jk} \sin(\delta_j - \delta_k + \theta_{jk}), \tag{5}$$

Where: V_k and V_j are the voltage magnitudes (V) at buses k and j, respectively.δ_k and δ_j are the voltage phase angles at buses k and j respectively.Y_{jk} and θ_{jk} are, respectively, the magnitude and angle of the admittance of the line connecting buses j and k together. N is the number of buses in the system.

It is important to note that the constraints given in Equations (2) and (3) are the constraints considered for this work. The selection of constraints depend on the level of power system security to be achieved. The constraints of Equation (2) must be satisfied, unconditionally, if afeasible solution is to exist (Dommel and Tinney, 1968; Sun *et al*.,1984). The constraints of Equation (3) are part of the most essential in power systems operation (Acha *et al*., 2004) .

INCLUSION OF RES IN OPF PROBLEM

An OPF algorithm based on the Newton-Raphson solution method has been developed by (Sun *et al.,* 1984; Acha *et al.,* 2004) to solve the problem stated in Equations (1) to (3). The solution method requires the conversion of the OPF problem which is a constrained optimisation problem into an unconstrained one with the introduction of Lagrangian function and multipliers. In this approach, the Lagrangian function for real and reactive powerflows is modelled as an equality constraint, given by Equation (6) (Acha *et al.,* 2004; Sun *et al.,* 1984). The first partial derivative of the Lagrangian with respect to considered variables are found and the resulting equations equated to zero. The sets of resulting equations are non-linear and a Newton Raphson's approach of solving non-linear problem was adopted. In cases of inequality constraints violations, limits are enforced according to the criteria given in in Equation (6) (Sun *et al.,* 1984; Acha *et al.,* 2004).

$$L(z,\lambda) = F_T + \sum_{k=1}^{N} \lambda_{pk}\left(P_k + P_{dk} - P_{gk}\right) + \sum_{k=1}^{N} \lambda_{qk}\left(Q_k + Q_{dk} - Q_{gk}\right), \tag{6}$$

Where:λ_{pk} and λ_{qk} are the Lagrangian multipliers related to the real and reactive power balance equations respectively.

The OPF algorithm (Acha *et al.,* 2004; Sun *et al.,* 1984) was extended to include the models of various FACTS devices (Acha *et al.,* 2004). Examples of FACTS devices considered are static var compensator (SVC), thyristor-controlled series compensator (TCSC), unified power flow controller (UPFC) and STATCOM. This algorithm was used to carry out the OPF analysis of the Nigerian network including STATCOM and UPFC by (Komolafe and Lawal, 2015) . In a bid to study the impact of RES on the Nigerian power network, this paper extends the OPF algorithm to include RES as against any FACTS devices.

The RES is expected to be connected to an existing bus in this work, so, the inclusion of RES in the OPF problem introduces two additional variables into the Lagrangian function. These variables are the active and reactive power output of the RES.

If RES is introduced at bus k, the power flow mismatch equations at this bus are modelled in the Lagrangian function as an equality constraint and are given in Equation (7).

$$L_{RES}(z,\lambda) = \lambda_{pk}(P_k + P_{dk} - P_{RES}) + \lambda_{qk}(Q_k + Q_{dk} - Q_{RES}) \tag{7}$$

where:

P_{RES} and Q_{RES} are the active and reactive output power of the RES at bus k. the value of P_{RES} is assumed to be a known parameter in the OPF problem and Q_{RES} is given as:

$$Q_{RES} = Q_k + Q_{dk} \tag{8}$$

Since bus k is an existing bus, the gradient vector and the Hessian matrix of the existing algorithm has catered for the partial derivatives of Equation (7) with respect to the Lagrangian multipliers, voltage magnitudes and angles at all buses (Komolafe and Lawal, 2015). However, the first partial derivatives of Equation (10) with respect to Lagrangian multipliers as contributed by RES are given as:

$$\frac{\partial L_{RES}(z,\lambda)}{\partial \lambda_{pk}} = -P_{RES} \tag{9}$$

$$\frac{\partial L_{RES}(z,\lambda)}{\partial \lambda_{qk}} = -Q_{RES} \tag{10}$$

Equations (9) and (10) are respectively added to the elements that correspond to λ_{pk} and λ_{qk} in the gradient vector. The elements of Hessian matrix are not affected by RES inclusion since the partial derivative of Equations (9) and (10) equals zero.

The inequality constraints of the bus with RES is handled the same way all other inequality constraints are handled (Sun, *et al.,* 1984;Acha *et al.,* 2004). After careful considerations of the additions introduced by the RES into the OPF solution algorithm, an extension has been done to the existing OPF MATLAB program to capture the inclusion of RES in the OPF formulation. The shape with fill in the flow chart of Figure 1 shows the addition in the algorithm.

RESULTS AND DISCUSSION

In this work, the three hydro stations (i.e. Shiroro, Jebba and Kainji) has been assumed to be optimally dispatched while the OPF procedure is used to dispatch the nine thermal stations (Komolafe and Lawal, 2015). However, 50 MW out of the reported RES potentials of Kano, Damaturu and Yola is used

in the system to test the effect of RES on the system. Three cases are considered for this study:
Case A: Nigerian OPF analysis without STATCOM (Komolafe and Lawal, 2015).
Case B: Nigerian OPF analysis with STATCOM only (Komolafe and Lawal, 2015).
Case C: Nigerian OPF analysis with RES only.

The cost coefficients of the thermal stations of the Nigerian system are given in Table 1. These are arrived at by a best curve fits of the thermal plants actual operating cost data during the year 2011 in a least square sense.

Table 2 compares various OPF parameters of the system for different cases. It could be inferred from Table 2 that, despite the RES contributing about 4% to the total real power generation, the OPF solution has reduced the total real power requirements from all the thermal generating station (GS) by 9.04%. This reduction further led to the reduction of both the cost of generation and active loss by 9.23% and 27.4%, respectively. It is obvious that the reduction in total real power generation and active loss for cases B and C are closely comparable.

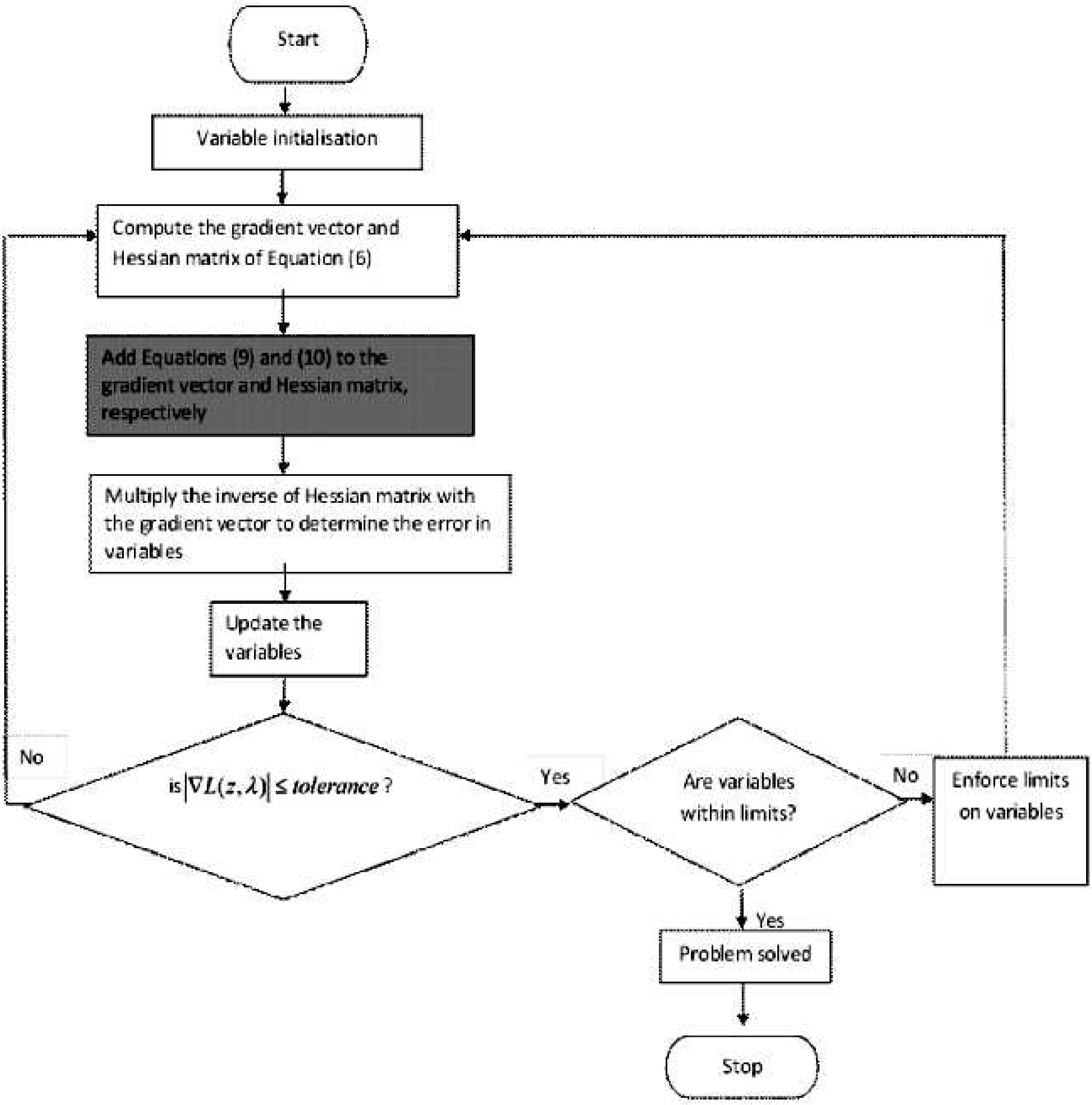

Figure 1. Flow chart showing the inclusion of RES into the OPF algorithm

Table 1: Fuel cost coefficient of the Nigerian thermal generators

Bus Name	**a (₦/hr)**	**b (₦/MWh)**	**c (₦/MW^{2}h)**
Egbin TS	221195.1	1095.322	0.54
Olorunsogo TS	53571.34	540.8642	3.82625
Omotosho TS	2546.284	1191.767	9.12229
Delta TS	90564.26	537.7682	2.79867
Sapele TS	67975.76	491.0473	4.46701
Geregu TS	180461.1	348.2421	2.04649
Okpai TS	10079.52	1803.967	0.01471
Afam TS	127392.7	485.7949	2.53965
Asco TS	13548.85	1663.612	0.5556

Note: TS means Thermal Station

Just like for case B, It is also clear that the maximum and minimum voltage magnitudes for case C are now within the tolerable limits of ±5% of 1.00pu. A comparison of the voltage magnitude of the buses si gnificantly affected by the inclusion of RES is presented in Figure 2. It can be observed that the voltage magnitude for these buses has significantly improve for cases B and C. This is as a result of both the RES and STATCOM having the ability to optimally readjust the reactive power settings in the system. This readjustment is achieved with reactive power injection at Kano and reactive power absorption at Damaturu and Yola. For case B, reactive power of 60 MVAR was injected at Kano while 70 MVAR was absorbed at Damaturu and Yola. These values were predetermined and not optimal (Komolafe and Lawal, 2015). In case C, an optimal reactive power (Q_{RES}) value of 95.33 MVAR has been injected by the RES at Kano while 86.22 MVAR and 89.83 MVAR are, respectively, absorbed by the RES at Damaturu and Yola.

Table 2: Comparison of some OPF parameters

Total Real Power generated (MW)	3798.75	3776.64	3771.75
Total Thermal GS generation (MW)	1957.27	1935.16	1780.27
Net Reactive Power generated (MVAR)	817.141	905.581	776.474
Cost (₦/hr)	3,273,215.36	3,233,945.29	2,971,184.56
Total active loss (MW)	98.7224	76.6076	71.7175
Total reactive loss (MVAR)	742.938	591.938	540.697
Maximum voltage magnitude (pu.) with location	1.4048 at	1.0475 at Shiroro GS	1.0481 at
Minimum voltage magnitude (pu.) with location	0.8499 at	0.9769 at	0.9755 at Damaturu
No of iterations			

Figure 3 presents the active generation of the thermal stations for the cases considered. While the outputs of all other thermal GS decreased for cases B and C, the output for Okpai GS increased for both cases. The output of Okpai GS for case C increased six times the base case value as shown in Table 3. Unlike case B, where only the active power at Okpai GS and Asco GS presented significant changes, case C shows that RES significantly changed the active generation of all the thermal stations. This is because, the RES has optimally changed the real power distribution in the system. This affected the power dispatch of thermal generators and power flows through the transmission lines.

A comparison of the real power bus marginal costs for the cases considered is shown in Figure 4. Unlike for cases A and B (whose values are close), it is obvious that the bus marginal cost for case C is lesser for all buses. This is an indication that, if this will be used for electricity pricing, the inclusion of RES could lead to reduction in electricity tariff for all buses in the system.

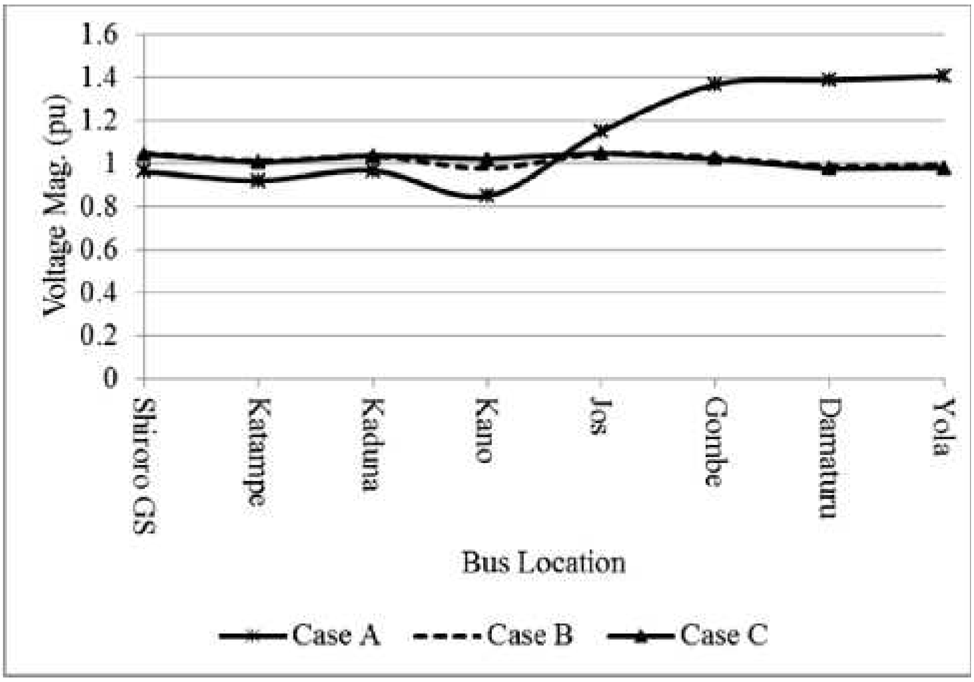

Figure 2: Comparison of voltage magnitude for different cases

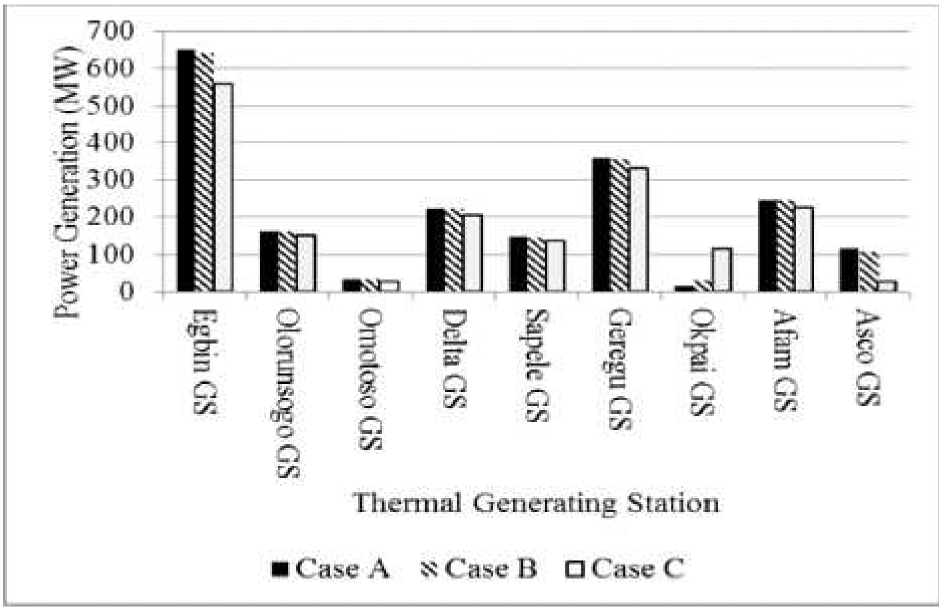

Figure 3: Comparison of active generation of the thermal stations

Table 3. Comparison of percentage change (%Δ) in active generation of the thermal station

Thermal GS	**%Δ for case B**	**%Δ for case C**	**Thermal GS**	**%Δ for case B**	**%Δ for case C**
Egbin	1.801	14.15	Geregu	0.891	6.994
Olorunsogo	1.006	7.902	Okpai	-79.8	-606.4
Omotoso	2.114	16.59	Afam	1.167	9.182
Delta	1.015	7.924	Asco	9.778	76.76
Sapele	0.987	7.752			

NB: Positive and negative percentage change, respectively, show a decrease and increase in generation.

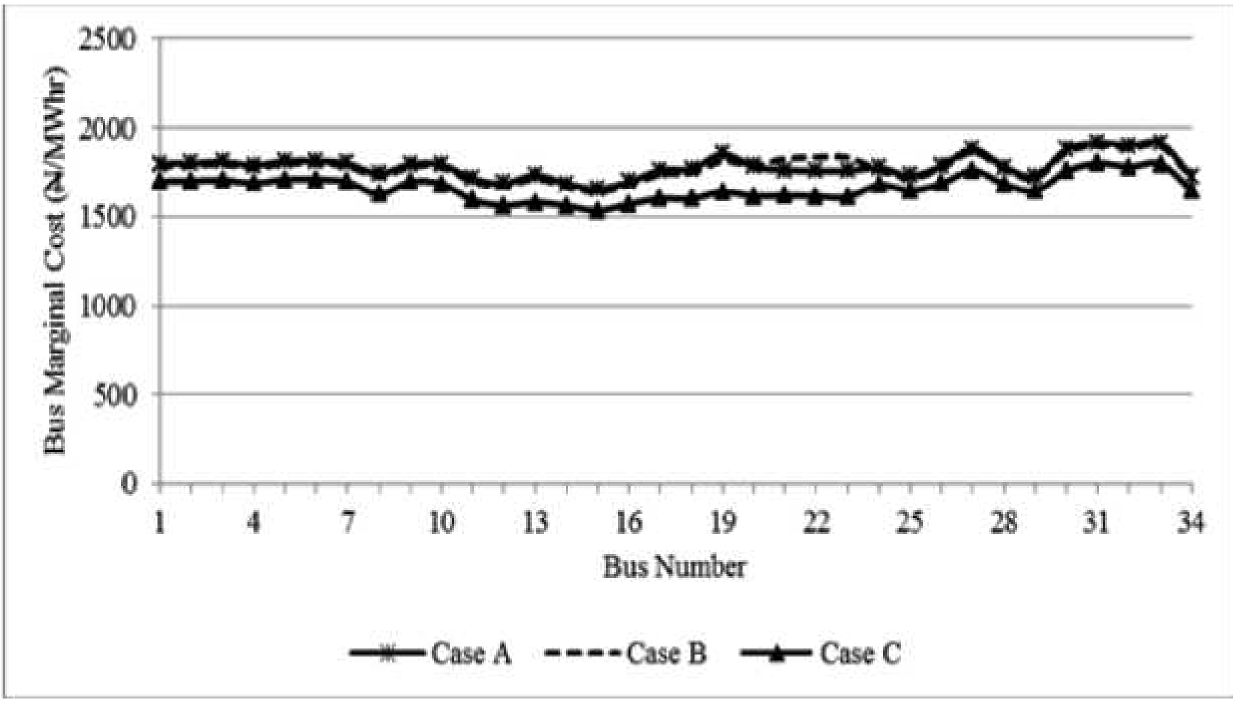

Figure 4: Comparison of real power bus marginal cost for different cases

CONCLUSION

An extension has been done to an existing OPF solution algorithm to capture the inclusion of RES. It has been shown that the inclusion of RES introduced two additional variables into the OPF problem. The solution algorithm has been used on the 330-kV Nigerian network to study the effect of RES on some buses to improve the system. The locations of the buses considered are Kano, Damaturu and Yola. The results compared the OPF analysis of the network with and without RES and STATCOM. The results showed that there exist some close similarities in the system with STATCOM and RES. And this is as a result of both having the ability to provide reactive support. But since RES is an active power source, it is able to reduce the fuel cost used for generation by the thermal generators, thereby reducing the overall bus marginal cost. Unlike the predetermined reactive support offered by STATCOM, it is also worthy of note that the reactive support offered by RES in this work is optimised. This study has successfully showed that optimal harnessing of the RES potential of the country will increase the amount of available energy for use, reduce the cost incurred on fuel, reduce active and reactive power loss, reduce electricity tariff and improve voltage profile of the network.

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