OPTIMAL POWER FLOW ANALYSIS OF NIGERIAN POWER NETWORK INCLUDING FACTS DEVICES

O. A. Komolafe[1] *and M. O. Lawal*[2]

1. Department of Electronic and Electrical Engineering, ObafemiAwolowo University, Ile-Ife, Nigeria.
2. Department of Electrical and Electronic Engineering, Osun State University, Osogbo, Osun State, Nigeria.

Abstract

This paper presents results of Optimal Power Flow (OPF) analysis of the Nigerian 330-kV power system network, with FlexibleAlternatingCurrentTransmissionSystem (FACTS) devicesincluded. The Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) data were simultaneously incorporated into an existing Newton-based OPF algorithm. The algorithm was applied to solve the Nigerian 34-bus power system. The hydro units were assumed to have been optimally dispatched while the OPF was used to dispatch the thermal plants. The OPF results without FACTS devices showed that the power network operated at a cheaper generation cost of 3,268,518.64₦/h when compared with the generation cost for the conventional power flow at 3,459,837.46₦/h. The results also showed that the incorporation of STATCOM and UPFC improved the overall system performance when compared with the solution witheither of these devices on the network.

Keywords: optimal power flow, real and reactive power flow, voltage magnitude, Newton-Raphson solution technique, Nigerian 34-bus power system

1.0 NOMENCLATURE

z: vector of power flow variables.

V_k, V_{cR}, V_{vR}, δ_k, δ_{cR}, δ_{vR}: voltage magnitudes and angles at bus k, series and shunt source converters.

V_m, V_l, δ_m, δ_l: voltage magnitudes and angles at buses m and l

Y_{ml} and θ_{ml}: magnitude and angle of the element of the bus admittance matrix that relate to buses m and l

X_{VR} and b_{VR}: shunt source converter reactance and susceptance respectively.

B_{cml}: susceptance of the transmission line that connects buses m and l

λ_{pk}, λ_{pm}, λ_{qk}, $\lambda_{qm}\lambda_{pvR}$, λ_{qvR}, λ_{pml}, λ_{qml}, λ_{sh}: Langrange multipliers relating to the active and reactive power balance equations at bus k, series and shunt source converter.

P_{dk}, Q_{dk}: the active and reactive power load at bus k respectively.

P_{gk}, Q_{gk}: scheduled active and reactive power generations at bus k respectively.

Q_{gVR}: specified injected or absorbed reactive power by the shunt source converter.

P_{sp}, Q_{sp}: specified active and reactive power flow through transmission line m-l.

2.0 INTRODUCTION

Electric utilities worldwide are faced with the challenges of providing their customers with secure and continuous supply of energy at competitive prices. Increased electric power demand, increased cost of power generation and the inability to obtain right of way for further expansion of the transmission lines are some of these challenges. In power systems, consumers are in control of how much power they use and they continuously anticipate that amount of power to be available on demand.

OPF solution is a tool that can simultaneously assist the power utilities to cater for the problem of increase in demand in electric energy and cost of energy generation. This study ensures that at any given period, generation must track both the customers' demands and transmission line losses while optimizing the fuel cost which is the objective function. The OPF problem was defined in early 1960s to simultaneously solve the power flow problem and automatically performs a steady-state control of some variables so as to optimize some operating conditions while maintaining a satisfactory system performance in terms of limits on output of generation and transmission equipment [1]-[2].

On the other hand, FACTS devices when installed are capable of strengthening the network and increasing its transmission capability. FACTS devices are specially designed power electronic devices for power system control. These devices are used to enhance the operation of the existing generation and transmission systems capability and to make power systems operation more robust and economical. The main objectives of FACTS controller are to control power flow on transmission lines,provide reactive power support for voltage control, improve power system stability and quality, and interconnect renewable and distributed generation and storages [3]. Examples of FACTS controllers for steady-state operation can be found in [3, 4].

Since OPF problems are very complex mathematical problems, researches had been done on the application of different numerical solution techniques to the problem. Some of these methods are Gradient [1], Newton-Raphson [2, 4, 5], Linear, Non-Linear and Quadratic Programming [6. 7, 8], Interior Point [9] and the Artificial Intelligent methods which include the Particle Swarm [10], Evolutionary Programming [11], Genetic Algorithm [12], Ant Colony Optimization [13] etc. A comprehensive survey of OPF methods with and without the incorporation of FACTS devices is given in [14]. The Newton-Raphson's method has been chosen for this work because of its rapid convergence characteristics. This property is especially useful for power system applications because an initial guess near the solution is easily attained. System voltages will be near rated values and generator outputs can be estimated from historical data [5].

Consideration of FACTS devices in the OPF problem had been given much attention in the past with most of the study considering the effect of one type of FACTS device on the network at a time. Examples of such FACTS devices that have been considered for OPF analysis are the Static VarConpensator (SVC) [15, 16, 17], Thyristor-Controlled Series Compensator (TCSC) [17, 18, 19] , UPFC [16,20], High Voltage Direct Current - Voltage Sourced Converter (HVDC-VSC) [21] and Interline Power Flow Controller (IPFC) [22]. In reality, situations may require the usage of different types of FACTS devices at the same time but various studies have not considered this for the OPF study. This work considers the inclusion of STATCOM and UPFC in OPF at the same time instance in a single framework to explore the benefits of OPF and both devices.

A brief survey of past works carried out on Nigeria power system network showed that [23] did a short term load forecast analysis for the Nigerian electrical power systems using Artificial Neural Network. The solution gives load forecast one hour in advance. [24] studied the oscillatory mode of the system using three methods which are the; Prony method, Eigen System Realization algorithm and the matrix pencil. The study established that the time-varying dynamic response of the network to a disturbance shows several electromechanical oscillatory modes with three different methods. Power Flow (PF) analysis of the system was done by [25-26]; the work of [25] considered the effect of the inclusion of STATCOM, HVDC-VSC and UPFC for voltage magnitude control, active and reactive power flow control on the 330-kV grid of the system. [26] considered both the 330 kV and 132 kV buses but assumed and presented all the buses to be operating at 330 kV. [27] also performed PF analysis on the system considering the existing system and the possible fortification that can be done on the system to improve its efficiency. [28]- [30] carried out, the real or reactive power dispatch using power flow solution technique for an optimal power dispatch. In optimal power dispatch, voltage magnitude of all generator buses are set to a fixed value throughout the solution process [29] while in OPF, voltage magnitude of the generator buses is considered as a control variable in achieving an optimal result [4]. The work of [31], considered the best location for Unified Power Flow Controller (UPFC) for voltage support without the consideration of any form of optimization. It should be noted that none of these works focused on the application of OPF with FACTS devices on the network. This study will focus on a combination of the advantages of applying both OPF and FACTS devices to the Nigerian power system network using Newton-based solution technique.

3.0 OPF PROBLEM DEFINITION

An OPF algorithm based on the Newton technique including SVC and TCSC had been developed by [17]. This paper extends the algorithm to include the combined model of STATCOM and UPFC.

3.1 Inclusion of STATCOM and UPFC in the OPF Equations

The inclusion of FACTS devices into the Newton-based OPF solution introduces additional variables into the augmented Lagrangian equation which in turn increases the number of elements in the gradient vector and Hessian matrix. In a previous work [17], a Newton-Based OPF algorithm including SVC and TCSC was addressed. Using the same method, an extension was made to include the mathematical representation of both STATCOM and UPFC at the same time instance.

3.1.1 Static Synchronous Compensator (STATCOM)

The STATCOM model as shown in Figure 1 consists of a Voltage Source Converter (VSC) and the associated shunt-connected transformer. In principle, it performs the same voltage regulation function as the SVC but in a more robust manner because, unlike the SVC, its operation is not impaired by the presence of low voltages [4].

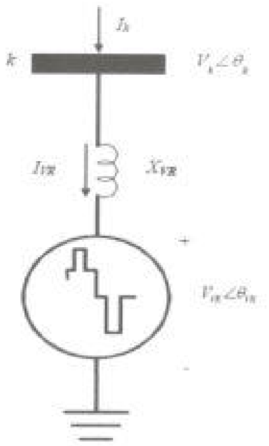

Figure 1: Static Synchronous Compensator (STATCOM) equivalent circuit [4].

Based on Figure 1, the real and reactive power flow is given as [4];

at bus k, the active and reactive power outputs are given as,

$$P_k = b_{VR} V_k V_{VR} \sin(\delta_k - \delta_{VR}) \tag{1}$$

$$Q_k = b_{VR} V_k^2 - b_{VR} V_k V_{VR} \cos(\delta_{VR} - \delta_k) \tag{2}$$

At the source converter, the active and reactive power outputs are

$$P_{VR} = b_{VR} V_K V_{VR} \sin(\delta_{VR} - \delta_K) \tag{3}$$

$$Q_{VR} = b_{VR} V_{VR}^2 - b_{VR} V_K V_{VR} \cos(\delta_K - \delta_{VR}) \tag{4}$$

$$b_{VR} = \frac{1}{X_{VR}}$$

Since no real power flow is expected to exist between STATCOM and bus k, P_{VR} is zero.

The power flow mismatch equations at bus k and source converter of the STATCOM are modelled in the Lagrangian function as an equality constraint and are given in eqn. (5).

$$L_{STATCOM}\ (z,\lambda_i) = \lambda_{pk}(P_k + P_{dk} - P_{gk}) + \lambda_{qk}(Q_k + Q_{dk} - Q_{gk}) + \lambda_{qVR}(Q_{vR} - Q_{gVR}) \tag{5}$$

The inclusion of STATCOM into the OPF formulation introduces two additional variables which are the magnitude and phase angle of the voltage of the source converter (V_{VR} and δ_{VR}).

The representation of the gradient vector (∇_{STAT}) and the Hessian matrix (H_{STAT}) due to the inclusion of STATCOM is given as;

$$\nabla_{STAT} = \begin{bmatrix} \nabla_z L_{STAT} \\ \nabla_\lambda L_{STAT} \end{bmatrix} \tag{6}$$

$$\nabla_z L_{STAT} = \frac{\partial L_{STAT}}{\partial z} = \begin{bmatrix} \frac{\partial L_{STAT}}{\partial \delta_k} & \frac{\partial L_{STAT}}{\partial \delta_{VR}} & \frac{\partial L_{STAT}}{\partial V_k} & \frac{\partial L_{STAT}}{\partial V_{VR}} \end{bmatrix}^T \tag{7}$$

$$\nabla_\lambda L_{STAT} = \frac{\partial L_{STAT}}{\partial \lambda} = \begin{bmatrix} \frac{\partial L_{STAT}}{\partial \lambda_{pk}} & \frac{\partial L_{STAT}}{\partial \lambda_{pVR}} & \frac{\partial L_{STAT}}{\partial \lambda_{qk}} & \frac{\partial L_{STAT}}{\partial \lambda_{qVR}} \end{bmatrix}^T \tag{8}$$

$$H_{STAT} = \begin{bmatrix} \frac{\partial^2 L_{STAT}}{\partial^2 z} & \frac{\partial^2 L_{STAT}}{\partial z \partial \lambda} \\ \frac{\partial^2 L_{STAT}}{\partial \lambda \partial z} & 0 \end{bmatrix} \tag{9}$$

$$\frac{\partial^2 L_{STAT}}{\partial \lambda \partial z} = \left[\frac{\partial^2 L_{STAT}}{\partial z \partial \lambda} \right]^T \tag{10}$$

The elements of z involved in the partial differentiation are the voltage magnitude V and voltage phase angle δ.

For every STATCOM included, two rows will be added to the gradient vector and two rows and columns will be added to the Hessian matrix of the base case OPF. The differentiation relating to bus k in both the gradient vector and the Hessian matrix described above were added to their respective position in the base case OPF gradient vector and Hessian matrix. After all necessary augmentation, the solution process described in [17] was followed.

V_{VR} has upper and lower limits and it was handled the same way all other limits on voltage magnitudes were handled [17].

3.1.2 Unified Power Flow Controller (UPFC)

The UPFC model used for this study is shown in Figure 2a [20]. It consists of two VSCs and a unified control system. It has the ability to simultaneously control the active and reactive power flow together with the voltage magnitude at the UPFC terminals. The controller may be set to control one or more or none of these parameters [4]. The equivalent circuit of the UPFC when used on the transmission line is shown in Figure 2b [4] where P_{ml} and Q_{ml} are respectively the active and reactive power flow required through line m-l. P_{ml} and Q_{ml} are given as

$$P_{ml} = -V_m^2 Y_{ml} \cos\theta_{ml} + V_m V_l Y_{ml} \cos(\delta_m - \delta_l - \theta_{ml}) \tag{11}$$

$$Q_{ml} = V_m^2 Y_{ml} \sin\theta_{ml} + V_m V_l Y_{ml} \sin(\delta_m - \delta_l - \theta_{ml}) - 0.5 B_{cml} V_m^2 \tag{12}$$

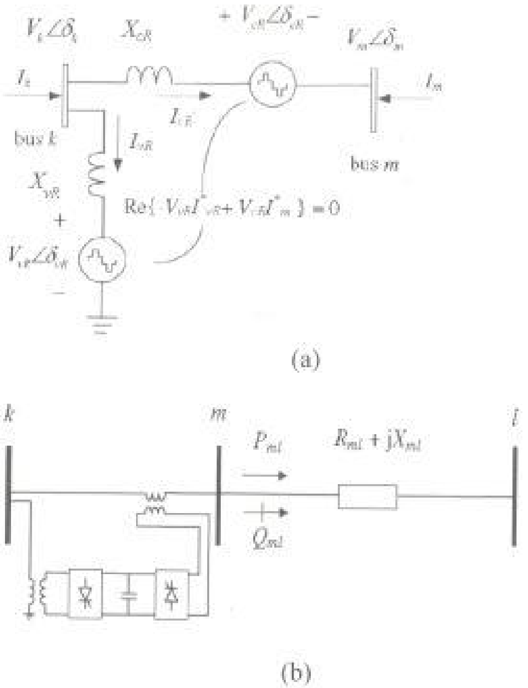

Figure 2: Unified Power Flow Controller (UPFC). (a) equivalent circuit [20] (b) compensated transmission line [4].

Based on figure 2, the active and reactive power equations are given as [20];

at bus k

$$P_k = V_k V_m B_{km} \sin(\delta_k - \delta_m) + V_k V_{cR} B_{km} \sin(\delta_k - \delta_{cR}) + V_k V_{vR} B_{vR} \sin(\delta_k - \delta_{vR}) \quad (13)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\delta_k - \delta_m) - V_k V_{cR} B_{km} \cos(\delta_k - \delta_{cR}) - V_k V_{vR} B_{vR} \cos(\delta_k - \delta_{vR}) \quad (14)$$

at bus m

$$P_m = V_k V_m B_{km} \sin(\delta_m - \delta_k) + V_m V_{cR} B_{mm} \sin(\delta_m - \delta_{cR}) \quad (15)$$

$$Q_m = -V_m^2 B_{mm} - V_k V_m B_{km} \cos(\delta_m - \delta_k) - V_m V_{cR} B_{mm} \cos(\delta_m - \delta_{cR}) \quad (16)$$

at the series source converter

$$P_{cR} = V_k V_{cR} B_{km} \sin(\delta_{cR} - \delta_k) + V_m V_{cR} B_{mm} \sin(\delta_{cR} - \delta_m) \quad (17)$$

$$Q_{cR} = -V_{cR}^2 B_{mm} - V_k V_{cR} B_{km} \cos(\delta_{cR} - \theta_k) - V_m V_{cR} B_{mm} \cos(\delta_{cR} - \theta_m) \quad (18)$$

at the shunt source converter

$$P_{vR} = V_k V_{vR} B_{vR} \sin(\delta_{vR} - \delta_k) \quad (19)$$

$$Q_{vR} = -V_k^2 B_{vR} - V_k V_{vR} B_{vR} \cos(\delta_{vR} - \delta_k) \quad (20)$$

$$B_{kk} = B_{mm} = -B_{km} = \frac{1}{X_{cR}} \quad , B_{vR} = \frac{1}{X_{vR}}$$

the active power supplied to the shunt converter, P_{vR}, is assumed to be equal to the active power demanded by the series converter, P_{cR}. This is shown as;

$$P_{vR} + P_{cR} = 0 \quad (21)$$

The Lagrangian function of the UPFC is given as [4];

$$L_{UPFC}(z,\lambda) = \lambda_{pk}(P_k + P_{ck} - P_{gk}) + \lambda_{qk}(Q_k + Q_{ck} - Q_{gk}) + \lambda_{pm}(P_m + P_{dm} - P_{gm}) + \lambda_{qm}(Q_m + Q_{dm} - Q_{gm}) +$$
$$\lambda_{qvR}(Q_{vR} - Q_{gvR}) + \lambda_{pm}(P_m - P_{ss}) + \lambda_{qm}(Q_m - Q_{ss}) + \lambda_{ss}(P_{vR} + P_{cR}) \qquad (22)$$

The gradient vector (∇_{UPFC}) and the Hessian matrix (H_{UPFC}) due to the inclusion of UPFC are given as;

$$\nabla_{UPFC} = \begin{bmatrix} \nabla_z L_{UPFC} \\ \nabla_\lambda L_{UPFC} \end{bmatrix} \qquad (23)$$

$$\nabla_z L_{UPFC} = \frac{\partial L_{UPFC}}{\partial z} = \begin{bmatrix} \frac{\partial L_{UPFC}}{\partial \delta} & \frac{\partial L_{UPFC}}{\partial V} \end{bmatrix}^T \qquad (24)$$

$$\nabla_\delta L_{UPFC} = \frac{\partial L_{upfc}}{\partial \delta} = \begin{bmatrix} \frac{\partial L_{UPFC}}{\partial \delta_k} & \frac{\partial L_{UPFC}}{\partial \delta_m} & \frac{\partial L_{UPFC}}{\partial \delta_l} & \frac{\partial L_{UPFC}}{\partial \delta_{cR}} & \frac{\partial L_{UPFC}}{\partial \delta_{vR}} \end{bmatrix}^T \qquad (25)$$

$$\nabla_v L_{UPFC} = \frac{\partial L_{upfc}}{\partial V} = \begin{bmatrix} \frac{\partial L_{UPFC}}{\partial V_k} & \frac{\partial L_{UPFC}}{\partial V_m} & \frac{\partial L_{UPFC}}{\partial V_l} & \frac{\partial L_{UPFC}}{\partial V_{cR}} & \frac{\partial L_{UPFC}}{\partial V_{vR}} \end{bmatrix}^T \qquad (26)$$

$$H_{UPFC} = \begin{bmatrix} \frac{\partial^2 L_{UPFC}}{\partial^2 z} & \frac{\partial^2 L_{UPFC}}{\partial z \partial \lambda} \\ \frac{\partial^2 L_{UPFC}}{\partial \lambda \partial z} & 0 \end{bmatrix} \qquad (27)$$

$$\frac{\partial^2 L_{UPFC}}{\partial \lambda \partial z} = \begin{bmatrix} \frac{\partial^2 L_{UPFC}}{\partial z \partial \lambda} \end{bmatrix}^T \qquad (28)$$

The gradient vector and the Hessian matrix of the base case OPF were modified to respectively include equations (23) and (27). After this modification, the solution procedure described in [17] was also followed to achieve an optimal solution.

Limits on newly introduced voltage magnitudes were handled the same way as all other voltage magnitude limits [17].

4.0 APPLICATION TO NIGERIA 330-kV 34 BUS

The Nigerian 330-kV power system grid consists of 34 buses and 55 transmission lines which connect nine thermal generating stations and three hydro stations to various load points. The quadratic cost functions for the thermal generating units have been developed as the best curve fits to their actual operating cost data [32] during the year 2011 in a least square sense. Detail of how the calculation was carried out was presented in [33]. The cost coefficient is shown on Table 1.

5.0 RESULTS AND DISCUSSION

An existing Newton based OPF algorithm which included SVC and TCSC was modified to include both the STATCOM and UPFC model. This algorithm was used to solve the OPF problem for the Nigerian network discussed in section 4.0 above. The gradient, real power and reactive power mismatch tolerance considered for this work is 10^{-5}.

5.1 Results for 34-bus Nigerian System

In this case study, the hydro stations power allocations were dispatched at 95 per cent of their installed generation capacity [36]. The optimal power flow solution of this network converges in fifteen iterations to a total active generation of 3793.24 MW, total reactive generation of 778.99MVAR, active power loss of 93.21 MW and a generation cost of 3,268,518.64₦/h. In the contrary, the PF solution gives a total generation of 3792.91 MW, active power loss of 92.88 MW and the cost of generation is 3,459,837.46 ₦/h. though, there is no much difference in both the active power generation and loss but there seems to be a considerable difference in the cost of generation. Since the OPF is a cost minimization tool there is a savings of 191,318.82 ₦/hr in the cost of generation when compared to the PF solution. The maximum and minimum voltage magnitude limits at all buses are taken to be 0.9 pu.and 1.05 pu. respectively, except at the following buses; Kano: minimum limit set at 0.85 pu. Jos: maximum limit set at 1.15 pu.,Gombe, Damaturu and Yola: maximum limit set at 1.5 pu.

Table 1: Quadratic cost coefficient for the 34-bus Thermal stations

Bus no	Bus Name	a (₦/h)	b (₦/MWh)	c (₦/MW^{2}h)
1	Egbin	221195.12	1095.32	0.540
7	Olurunsogo	53571.34	540.86	3.826
9	Omotosho	2546.28	1191.77	9.122
24	Delta	90564.26	537.77	2.799
26	Sapele	67975.76	491.05	4.467
29	Geregu	180461.13	348.24	2.047
30	Okpai	10079.52	1803.97	0.015
33	Afam	127392.73	485.80	2.540
34	Asco	13548.80	1663.60	0.556

The bus parameter of the OPF solution is given in Table 2. It is observed that there exists a low voltage magnitude of 0.85 pu at Kano. This is as a result of the length of the transmission line (230-km) which connects Kano to Kaduna and the high demand at Kano (189.00 + j141.8 MVA). Similarly, the high voltage magnitude experienced at Jos, Gombe, Damaturu and Yola is also as a result of the length of the transmission line connecting Kaduna to Jos to Gombe to (Damaturu and Yola) which adds up to 642-km to Damaturu and 679-km to Yola. Also, the load at these buses is low with the lowest at Yola. High line capacitance has made a build-up of reactive power on the transmission-line and with the presence of low demand; there will be high voltage magnitude at these buses. Regulating these low and high voltage magnitude at the buses concern requires the help of reactive support. The type of reactive support considered in this work is the one provided by STATCOM.

Since the study is based on the simultaneous inclusion of STATCOM and UPFC, three STATCOM's were placed at Kano, Damaturu and Yola to regulate their voltage magnitude with the STATCOM connected to Kano supplying reactive power of 60 MVAR and the ones connected to Damaturu and Yola absorbing 70 MVAR each. One UPFC is also placed between Osogbo and Ikeja-West transmission line to control the active and reactive power flow together with possible voltage magnitude control at Osogbo. The power flow on the line was increased by 30 - j10 MVA from its OPF base case value of 193.189- j52.231 MVA. The voltage source converter of the UPFC is made to absorb 30 MVAR. The source converter impedance X_{VR} and X_{CR} considered for all the STATCOM's and UPFC is 0.1 pu. The upper and lower limits considered for V_{cR} are respectively 0.001 and 0.6pu. [4].The upper and lower limits for V_{vR} are 0.9 pu. and 1.05 pu respectively.

To study the benefit of including both the STATCOM and UPFC together in the system, four cases were considered; Case 1: OPF without FACTS devices, Case 2: OPF with STATCOM only, Case 3: OPF with UPFC only and Case 4: OPF with STATCOM and UPFC.

Table 3 compares different parameters for different cases. It can be noted from the table that cases 1 and 3 have almost the same parameters except for the total reactive generation and loss. This is as a result of the reactive power absorption at Osogbo where the UPFC is connected. The benefit derived from the inclusion of UPFC only in this system is just the power flow control which was done effectively. It can also be seen from this table, the improvement STATCOM has introduced into the system as indicated by cases 2 and 4.

If not for the simultaneous usage of these two devices, UPFC will only control the power flow of the line it's connected to, with high and low voltage magnitude still apparent on the system. Figure 3 (which compares the voltage magnitude of Osogbo and buses greatly affected by the device(s)) confirms this as it is clear that the voltage magnitude for cases 1 and 3 are almost equal while that for cases 2 and 4 are also very close to each other. It is important to note from Figure 3 that the voltage magnitude at Osogbo is not really affected for cases 3 and 4 even with its connection to UPFC. On the other hand, STATCOM has the ability to control the voltage magnitude without performing power flow control. Thus, the inclusion of both devices, has explored the benefit from both for the improvement of thesystem.

Table 2: Bus parameters for the 34-bus Nigerian power network without FACTS device(s)

Bus name	**Vol Mag (pu)**	**Vol Angle (deg)**	**λ_p (N/MWh) ×10**	**P_g (MW)**	**Q_g (MVAR)**
Egbings	1.0461	0	181.19	663.495	437.31
Aja	1.0418	-0.245	181.425	0	0
Ikejawest	1.0258	-1.088	182.214	0	0
Benin	1.0419	0.82	180.479	0	0
Akangba	1.0195	-1.451	182.589	0	0
Sakete	1.0211	-1.534	182.623	0	0
Olorunsogogs	1.044	-0.085	181.265	166.402	332.218
Osogbo	1.0355	6.695	175.556	0	0
Omotoshogs	1.0452	0.223	180.971	34.551	2.152
Ayede	1.02	0.829	180.643	0	0
Ganmo	1.0362	10.177	172.666	0	0
Jebba	1.0411	13.434	170.003	0	0
Shirorogs	0.9623	7.658	174.645	570	-214.229
Jebbags	1.0421	13.722	169.831	549.48	48.59
Kainjigs	1.0435	17.358	166.906	722	-117.785
Birninkebbi	1.0188	12.576	170.853	0	0
Katampe	0.9208	4.455	177.65	0	0
Kaduna	0.9674	2.666	178.231	0	0
Kano	**0.85**	-5.634	186.685	0	0
Jos	**1.1472**	-4.64	179.574	0	0
Gombe	**1.366**	-9.842	177.662	0	0
Damaturu	**1.3864**	-10.579	177.274	0	0
Yola	**1.4049**	-10.553	177.206	0	0
Deltags	1.0439	2.406	179.107	227.766	-17.31
Ajaokuta	1.0443	6.607	175.617	0	0
Sapelegs	1.0447	1.26	180.082	141.539	32.277
Onitsha	1.0295	-7.95	188.277	0	0
Aladja	1.041	1.791	179.646	0	0
Geregugs	1.0438	6.751	175.502	357.066	-112.858
Okpaigs	1.0444	-7.639	187.908	83.872	130.363
Alaoji	1.0296	-12.153	192.017	0	0
Newhaven	0.9971	-10.07	190.441	0	0
Afamgs	1.04	-11.829	191.658	244.299	287.208
Ascogs	1.044	6.733	175.519	32.773	-28.949

The shunt source converter parameters for both STATCOM and UPFC are shown in Table 4. It shows that STATCOM requires high voltage magnitude to regulate the low voltage magnitude at Kano to a high value and it requires low voltage magnitude to regulate the high voltage magnitudes at Damaturu and Yola to a low value. The series source converter voltage magnitude and angle for both cases are V_{cR} = 0.2635 pu., δ_{cR} = -66.3350 degree for case 3. V_{cR} = 0.2587 pu.,δ_{cR} = -66.3367 degree for case 4.

Table 5 and 6 respectively shows the percentage changes in active and reactive power flow of transmission lines connected to Osogbo and Ikeja-west. It can be observed that the inclusion of UPFC for both cases has not really altered the active power flow from its base case value but greatly affected the reactive power flow on some lines, especially the lines connected to Osogbo. This is as a result of the reactive power flow increase towards Osogbo and the reactive power absorption also at Osogbo.

Table 3: Comparison of results for different cases

Case no	Case 1	Case 2	Case 3	Case 4
Total Real Power generated(MW)	3793.24	3772.49	3793.5	3773.1
Total Reactive Power generated(MVAR)	778.987	869.267	798.287	896.89
Cost(₦/hr)	3,268,518.64	3,231,287.88	3,268,448.76	3,232,967.85
Total activeloss(MW)	93.21	72.46	93.47	73.0689
Total reactiveloss(MVAR)	701.68	560.742	705.843	567.233
No of iterations	15	13	12	12
Maximum voltage magnitude (pu.)	1.405	1.048	1.405	1.049
Minimum voltage magnitude (pu.)	0.8500	0.977	0.85	0.978

Table 4: Voltage magnitudes and angles of the shunt source converters

Case number	Case 2		Case 3		Case 4	
	Voltage Mag. (deg)	Voltage angle (pu)	Voltage Mag. (pu)	Voltage angle (deg)	Voltage Angle (pu)	Voltage Mag. (deg)
*Osogbo	-	-	1.007	6.078	1.005	6.33
**Kano	1.035	-2.815	-	-	1.036	-3.344
**Damaturu	0.913	-7.785	-	-	0.917	-8.299
**Yola	0.920	-7.594	-	-	0.924	-8.109

** The shunt source converter at this bus is that of the UPFC*
*** The shunt source converter at these buses is that of the STATCOM*

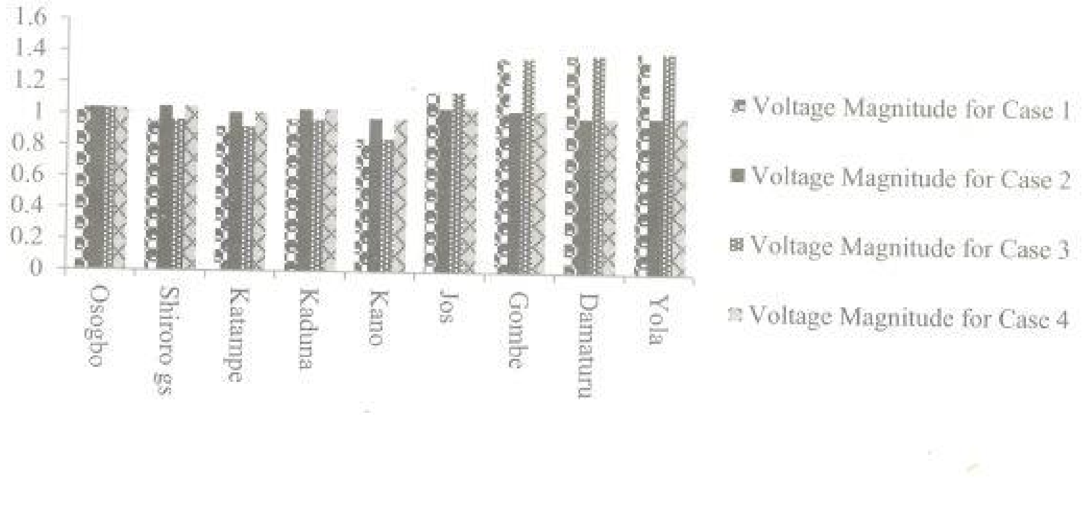

Figure 3: Comparison of voltage magnitude for different cases

Table 5: Comparison of percentage change in active power flow

From	To	%Δ for case 3	%Δ for case 4
*egbin gs	ikeja west	-1.611	-1.532
ikeja west	omotosho gs	**-6.399**	**-20.13**
**ikeja west	akangba	0.001	0.001
ikeja west	olorunsogo gs	**-7.625**	**-4.344**
ikeja west	Sakete	0	0
Osogbo	**ikeja west**	15.53	15.53
Osogbo	benin	-7.609	2.558
Osogbo	ayede	-5.889	-3.702
Osogbo	ganmo	**0.010**	**2.924**
**osogbo	jebba	0	**2.706**

Table 6: Comparison of percentage change in reactive power flow

From	To	%Δ for case 3	%Δ for case 4
*egbin gs	ikeja west	-0.031	-0.217
ikeja west	omotoso gs	**7.473**	**10.45**
**ikeja west	akangba	0.017	0.017
ikeja west	olorunsogo gs	**8.165**	**7.379**
ikeja west	Sakete	1.156	1.117
Osogbo	**ikeja west**	**19.15**	**19.15**
Osogbo	Benin	**1.010**	**2.922**
Osogbo	Ayede	**-66.95**	**18.33**
Osogbo	Ganmo	-23.61	-18.59
**osogbo	Jebba	-73.20	-56.90

***Note:** The line marked * is one of **three** lines connecting both buses and the line marked ** is one of **two** lines connecting both buses. The bolded line contains the UPFC. The bolded values are the percentage change in power flow towards the sending bus. Negative values show percentage reduction in power flow from base case*

6.0 CONCLUSION

A Newton-based method of solving the OPF problem of the Nigerian Power Network with and without the incorporation of FACTS devices was investigated and discussed in this work. An extension was made to incorporate the STATCOM and UPFC model into an existing OPF algorithm. A developed Newton-Based (OPF) algorithm incorporating STATCOM and UPFC was used to analyse the network. The objective function considered for this work is the cost of generating active power with the power balance equations as the equality constraints. The inequality constraints considered for this work are the real and reactive power generations and the nodal voltage magnitude. The result obtained showed that the OPF of the network, when compared with the power flow solution performed the function of minimizing the cost of generation. The incorporation of STATCOM and UPFC into the OPF algorithm regulated some power system parameters with no major alteration to system characteristics. STATCOM had performed the function of controlling the voltage magnitudes with the injection and absorption of reactive power into the system, this led to an overall improved network voltage profile. UPFC was shown to have flexibly controlled both the active and reactive power flow on a transmission line.

In summary, the developed algorithm for solving the Nigerian power network was able to achieve the minimization of power generation costs, together with the control of some power system parameters such as voltage magnitude and real power flow.

References

1. Dommel H. W. and Tinney W. 1968. OPF Solutions. IEEE Transaction on Power Apparatus and Systems. PAS-87(10): 1866–1876.
2. Sun D. I., Ashley B., Brewer B., Hughes A. and Tinney W. F. 1984. OPF by Newton Approach. IEEE Transactions on Power Apparatus and Systems, Volume PAS-103: 2864-2880.
3. Zhang X. P., Rehtanz C. and Bikash P. 2006. Flexible AC Transmission Systems: Modelling and Control. Springer-Verlag Berlin Heidelberg.
4. Acha E., Fuerte-Esquivel C. R., Ambriz Perez H. and Angelas-Camacho C. 2004. FACTS Modelling and Simulation in Power Networks, John Wiley and Sons Limited, England.
5. Weber J. D. 1997. Implementation of a Newton-Based OPF into a Power system simulation environment, M.Sc. Thesis at the University of Illinois. Urbana-Champaign.
6. Olofsson M., Andersson G. and Soder L. 1995. Linear Programming based OPF using second order sensitivities. IEEE Transactions on power systems. 10(3): 1691 – 1697.
7. Granelli G. P. and Montagna M. 2000. Security Constrained Economic Dispatch using dual Quadratic Programming. Electric Power System Research. Volume 56: 71-80.
8. Momoh J. A. and Zhu J. 2001. Multi-area powersystems economic dispatch using nonlinearconvex network flowprogramming. ElectricPower System Research.Volume 59: 13-20.
9. Capitanescu F., Glavic M., Ernst D. and Wehenkel L. 2007. Interior-point based algorithms for the solution of OPF problems. Electric Power Systems Research. Volume 77: 508–517.
10. Abido M. A. 2002. OPF using particle swarm optimization, Electrical Power and Energy Systems. Volume 24: 563-571.
11. Somasundaram P., Kuppusamy K. and Devi R. P. K. 2004. Evolutionary programming based security constrained OPF. Electric Power Systems Research. 72(2): 137-145.
12. Bakirtzis A. G.,Biskas P. N.,Zoumas C. E. and Petridis V. 2002. OPF by Enhanced Genetic Algorithm. IEEE Transactions on Power Systems. 17(2): 229-236.
13. Bouktir, T. and Slimani, L. 2005. OPF of the Algerian Electrical Network using an ant colony optimization method. The 9th IASTED International Conference on Artificial Intelligence and Soft Computing, Benidorm, Spain.
14. Pandya K. S. and Joshi S. K. 2008. A Survey of Optimal Power Flow Methods. Journal of Theoretical and Applied Information Technology. 450-457.
15. Ambriz-Pe´rez H., Acha E. and Fuerte-Esquivel C. R. 2000. Advanced SVC Models for Newton-Raphson Load Flow and Newton OPF Studies. IEEE Transaction on Power Systems, 15(1): 129–136.
16. Palma-Behnke R., Vargas L. S., Pérez J. R., Núñez J. D. and Torres R. A. 2004. OPF with SVC and UPFC Modelingfor Longitudinal Systems. IEEE Trans. Power Systems. 19(4): 1742–1753.
17. Komolafe O. A. and Lawal M. O. 2010. Newton-Based OPF Algorithm Incorporating SVC and TCSC. Ife Journal of Technology. 19(2): 33 - 37.
18. Ambriz-Pe´rez H., Acha E. and Fuerte-Esquivel C. R. 2006. TCSC-firing angle model for OPF solutions using Newton's method. Electrical Power and Energy Systems. Volume 28: 77–85.
19. Lee K. 2002. Optimal Sitting of TCSC for Reducing Congestion Cost by using Shadow Prices. Electrical Power and Energy Systems. Volume 24: 647–653.
20. Ambriz-Pe´rez H.,Acha E., Fuerte-Esquivel C. R. and De la Torre A. 1998. Incorporation of a UPFCmodel in an Optimal Power Flow using Newton's Method. IEE Proceedings on Generation,Transmissionand Distribution. 145(3): 336–344.
21. Pizano-Martinez A., Fuerte-Esquivel C. R.,Ambriz-Pe´rez H. and Acha E. 2007. Modelling of VSC-Based HVDC Systems for a Newton-Raphson OPF Algorithm. IEEE Trans. Power Systems, 22(4): 1794–1803.
22. Naresh-Babu A. V. andSivanagaraju S. A. 2012. New Approach for Optimal Power Flow Solution Based on TwoStepInitialization with Multi-Line FACTS Device. International Journal on Electrical Engineering and Informatics, 4(1): 173-185.
23. Adepoju G. A., Ogunjuyigbe S. O. A. and Alawode K. O. 2007. Application of Neural Network to Load Forecasting in Nigerian Electrical Power System. Pacific Journal of Science and Technology. 8(1): 68-72.

24. Venayagamoorthy, G. K., Aliyu, U. O., Chow, J. H. and Sanchez-Gasca, J. J. 2005. Modal Extraction with Three Different Methods for the Nigerian Power System. International Conference on Power Systems, Operation and Planning, Praia, Cape Verde. 61-66.

25. Adepoju G. A., Komolafe O. A. and Aborisade D. O. 2011. Power Flow Analysis of the Nigerian Transmission System Incorporating FACTS Controllers. International Journal of Applied Science and Technology. 1(5): 186-200.

26. Omorogiuwa E. andEmmanuel A. O. 2012. Determination of Bus Voltages, Power Losses and Flows in the Nigeria 330 kV Integrated PowerSystem. International Journal of Advances in Engineering & Technology. 4.(1): 94-106.

27. Izuegbunam F. I., Duruibe S. I. and Ojukwu G. G. 2011. Power Flow and Contingency Assessment Simulation of the Expanding 330KV Nigeria Grid Using Power World Simulator. Journal of Emerging Trends in Engineering and Applied Sciences. 2(6): 1002-1008.

28. Bakare, G. A. Aliyu, U. O., Venayagamoorthy, G. K. and Shu'aibu, Y. K. 2005. Genetic Algorithms Based Economic Dispatch with Application to Coordination of Nigerian Thermal Power Plants. IEEE Power System Society General Meeting. Volume 1: 551-556.

29. Alawode K. O. and Jubril A. M. 2010. Multiobjective Power Dispatch for the Nigerian Power Network. Ife Journal of Technology. Volume 19(2): 11-14.

30. Bakare G. A., Krost G., Venayagamoorthy G. K. and Aliyu U. O. 2007. Differential Evolution Approach for Reactive Power Optimization of Nigerian Grid System. IEEE Power System Society General Meeting. pp. 1-6.

31. Nwohu M. N. 2010. Optimal Location of Unified Power Flow Controller (UPFC) in Nigerian Grid System. International Journal of Electrical and Power Engineering, 4(1): 147-153.

32. Power Holding Company of Nigeria, PHCN. Generation and Transmission Grid Operations. National Control Center, NCC. Osogbo.

33. Lawal M. O. 2011. Development of a Newton-Based OPF Algorithm Incorporating FACTS devices. Unpublished Master Thesis, Department of Electronic and Electrical Engineering, ObafemiAwolowoUniversity, Ile-Ife, Osun State.