Optimization of Nigeria Power System Stability using Multiple Facts Placement

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Abstract:
This research considers placement of multiple FACTS device on Nigeria 52 Bus Network. Three methods were proposed for the analysis of this work. Eigen value voltage sensitivity analysis was used to locate the weakest Bus in the Network, while load flow and continuation power flow result were used to ascertain the state of the Network after the FACTS was added. For the purpose of the research, the FACTS device considered is Unified Power Flow Controller (UPFC). After the analysis, three weakest Bus was identified using eigen value analysis as Buses 6, 11 and 45, of which Bus 45 was more affected with the highest participation factor. Improvement was seen in only the real and reactive power losses using one or two UPFC, but, when three UPFCs were used, there is improvement in every aspect of the system. Using three UPFC shows that no Bus was violated, there was real and reactive power improvement, ability of the system to accept more load without much violation, and improvement of real and reactive power at the point of violation. This shows that it will be recommended that more than one FACTS device can be used for maximum impact in large networks like Nigeria 52 Bus Network.

Keywords: Transient stability, sensitivity analysis, optimization, Eigen-value, weakest bus.

1. INTRODUCTION

Power system has always been a big determinant to any Nation’s growth due to its use in almost every aspect of the Nation’s developmental process. Nigeria as a Nation has been experiencing a lot of setback, which has affected its economy in every area or aspect due to unavailability of power supply. The power problems have led to business collapse, loss of jobs, lack of investors and above all, collapse of the country’s economy. In a bid to improve the power system of Nigeria, several researches have been done and so many suggestions on ways to improve the generation, transmission and distribution lines have been given which have not still improved the power system to satisfy the consumers. Most of the suggestions have been on ways to increase the number of generating stations which can be seen as a long term project, though a realistic project if properly planned. This can be achieved using the natural resource, which is so abundant in the nation, and new emerging technologies. In a quest to improve on this areas, in 2010, the generation and distribution company were privatized which have yielded no solution due to the profit mindset of the investors without investment plan. In 2013, almost all of the six power generating plants and eleven distribution companies unbundled from Power Holding Company of Nigeria (PHCN) were eventually sold, there was high expectation that the new owners will bring a rapid end to frequent power outages, but due to majorly lack of generation to satisfy the demand of the country, there has not been a significant improvement [9]. To boost the generation, the Federal Government have decided to explore the natural resources which are so abundant and can easily be accessed. This if implemented as planned hopes to expand the Network up to 17 generators, 52 bus system. If the larger network is achieved which promises more than 10,000MW of electricity as against the 4600MW which can be achieved with the 28 bus system, the power system will achieve a significant improvement except if proper maintenance is not done. Though more generation is needed to stabilize the power system of Nigeria, the major factor which contributes to power system instability is reactive power Imbalance. In balancing the reactive power Flexible AC Transmission System (FACTS) devices have been used recently. This works in such a way that it either injects or absorbs power into the network to balance the active power due to the dynamic nature of power system. This will minimize the violation of the voltage and losses [1]. A power system is said to have entered a state of voltage instability when a disturbance causes a progressive and uncontrollable decline in voltage. Voltage instability and collapse will result to major system failures or black outs. Inadequate reactive power support from generators and transmission lines leads to voltage instability or voltage collapse. Basically, this paper hopes to investigate the voltage stability of power system with the new generating stations from the reserved energy resources connected to the grid at transmission level. The existing transmission grid will be simulated with and without new generating stations. The results will then be compared and relevant conclusions will be drawn from it. In transmission lines, congestion management is one of the most important issues for the operation of power system. The congestion is associated with one or more violations of the physical layer, operational and policy constraints under which grid operate. Placement of FACTS device for generation scheduling and load-shedding plays a crucial role in congestion management. FACTS devices are used to enhance the maximum load ability of the transmission system. FACTS increases the flexibility of the power system, makes it more controllable, and allows utilization of the existing network closer to its maximum capacity without jeopardizing the stability. It will aid more power to reach consumers with a shorter project implementation time and a lower investment cost [3]. Despite several methods used for stability analysis, this work hopes to explore more critical analysis on small signal dynamic stability analysis amongst other methods (load flow and continuation power flow) used for the power system.
stability and losses investigation. This method hopes to give a thorough investigation on the state of the Nigerian power system and the improvement in achieving our vision 2020.

2. LITERATURE REVIEW

The problems of Nigeria power have led to the meltdown on the economy of the Nation as power plays a vital role in the development of any Nation. Some argued that the problem is associated to the poor leadership of the Nation, while others believe that power have not attracted the proper investment it needs. Electricity generation and challenges in Nigerian Network reported that Nigeria has an estimated 176 trillion cubic feet of proven natural gas reserves, giving the country one of the top ten natural gas endowments in the world and the largest endowment in Africa [6]. Most of the recent problems sited on the National grid have been linked to poor transmission system maintenance. Though generation boosting is needed, but, without proper transmission maintenance, there could be problems associated to power delivery and optimization. An effective power delivery should be seen in its transmission losses and ability to accept more load without a collapse in the system. A paper was presented considering dynamic security assessment of the Nigeria 330 kV, 13 generation, 26 Bus power network [4]. It considered the installed capacity of the power system alongside the available capacity as well as network structure in terms of redundancy for flexibility. Some weak areas of the system were identified and the security status of the network assessed under large disturbance condition. Results match expectations as the system’s response to impressed contingencies were discussed. Feasible corrective measures proffered for improved system’s security. The researcher recommended FACTS device as one of the possible solutions to the poor Network. In recent times, more focus have geared towards improving the transmission system using Flexible AC Transmission Systems (FACTS) devices. A research was done which considered a comprehensive review on enhancement of power system stability such as rotor angle and frequency stability and voltage stability by using different FACTS controllers such as TCSC; SVC; SSSC; STATCOM; UPFC; IPFC in an integrated power system networks and the result showed best performance to be STATCOM and UPFC [5]. The modulation and control of power flow in transmission line using Static Synchronous Series Compensator (SSSC) is very important [10]. PWM techniques control for SSSC are conducted and control circuits are presented. In this research SSSC is used to investigate the effect of it in controlling active and reactive powers as well as damping power oscillations in the transient mode. Simulations are done in MATLAB/simulink environment. Two machine systems is used in this research along with SSSC for controlling power flow in the line and achieving the desired value for active and reactive power, also damping oscillations appropriately. Comparative performance of SVC (Static Var Compensator) and UPFC (Unified Power Flow Controller) for the improvement of transient stability of multi-machine system was also studied and analysis done with MATLAB software [7]. The UPFC is a more effective FACTS (Flexible AC Transmission System) device for controlling active and reactive power flow in a transmission line and power oscillation damping by controlling its series and shunt parameter. Simulation is carried out in MATLAB/Simulink environment for multi-machine system to analyze the effects of SVC and UPFC on transient stability system. The performance of UPFC is compared with SVC. The simulation results demonstrate the effective and robustness of the proposed UPFC for transient stability improvement of the system. Investigation was done on how UPFC affects the transmission system having series voltage and shunt current injection [8]. UPFC provides better results than other devices and its advantages are also discussed. Various features of UPFC are discussed and some of them include improvement of the system characteristics, power factor, and control of voltage and power flow thus providing the best transient and dynamic stability. UPFC is also used for improving the transient stability in power system. Simulation is done for various loads and system voltages.

3.0 METHODOLOGY

This research considered the 52 bus Networks and the impact of FACTS devices on the Network. The work considered the placement of FACTS device on the expanded Network for better performance. The 52 bus Nigerian network Fig. 1, was simulated using Power System Analysis Toolbox (PSAT) in MATLAB 7.9 of 2017. The FACTS device placement was on the lines along the weakest buses or the weakest buses. For the placement of any FACTS device, sensitivity analysis (Eigen value analysis) was used to determine the weakest buses for proper placement. Three power system analyses were conducted in this research for proper analysis of the voltage stability for different conditions. These methods are: load flow study, continuation power flow study and small signal stability analysis. These methods accounts for both the static stability analysis and dynamic stability analysis. This will aid the proper planning and maintenance of the Network.

3.1. NIGERIAN 330KV POWER NETWORK

The Network to be considered is the Nigeria 330kV Network. This study will account for the performance of the 52 bus Network, Fig.1. The Network comprises of the newly integrated and the ongoing projects which has up to 17 generating stations and additional load to the National grid. The present Network reflects the upgrade from former 10 generating stations which further expanded the Network from 28 bus system to 52 bus system. The total power generated from the old 28 bus Network is about 4,600MW, whereas the expanded Network promises approximately 10,000MW of power.

![Figure 1. The Nigerian 330kV, 52 bus network.](image)

3.2 POWER FLOW ANALYSIS

Power flow analysis will account for the static behaviour of the Network (i.e. the behavior of the Network at constant load and generation). This investigation ascertains the behavior of the Network for a particular or present condition. The method adopted for this research will be Newton-Raphson power flow method. There are two methods of solution for the load flow using Newton-Raphson method. The first method uses
rectangular coordinates for the variables, while the second method uses the polar coordinate form, but the polar coordinate method is widely used. The equation for the complex power at node i in the polar form is given in equation 1. Equations 3 and 4 gives the active and reactive powers at bus i. Reproducing this equations gives

\[
P_i = V_i Y_i V_i^* \quad (1)
\]

\[
S_i = \sum_{k=1}^{n} (V_i Y_{ik} V_k^*) \quad (2)
\]

\[
P_i = \sum_{k=1}^{n} (V_i Y_{ik}) \cos(\delta_i - \delta_k - \theta_{ik}) \quad (3)
\]

\[
Q_i = \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (4)
\]

Equations 3 and 4 can also be written as

\[
P_i = (V_i Y_{ii}) \cos(\theta_{ii}) + \sum_{k=1}^{n} (V_i Y_{ik}) \cos(\delta_i - \delta_k - \theta_{ik}) \quad (5)
\]

\[
Q_i = -(V_i Y_{ii}) \sin(\theta_{ii}) + \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (6)
\]

The off-diagonal and diagonal elements of \( H \), \( N \), \( M \), \( L \) are determined by differentiating equation 10 with respect to \( \delta \) and \( V \). Off-diagonal elements of \( H \),

\[
H_{ik} = \frac{\partial P_i}{\partial \delta_k} = \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) , \quad i \neq k \quad (10)
\]

Diagonal elements

\[
H_{ii} = \frac{\partial P_i}{\partial \delta_i} = -V_i \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (11)
\]

Using equation 11, we have

\[
\frac{\partial P_i}{\partial \delta_i} = -(Q_i + V_i^2 Y_{ii} \sin(-\theta_{i})) \quad (12)
\]

\[
H_{ii} = -Q_i - V_i^2 Y_{ii} \sin(-\theta_{i}) = -Q_i - B_{ii} V_i^2 \quad (13)
\]

The off-diagonal and diagonal elements of \( N \) are given by

\[
\frac{\partial Q_i}{\partial V_i} = V_i Y_{ik} \cos(\delta_i - \delta_k - \theta_{ik}) \quad (14)
\]

\[
\frac{\partial Q_i}{\partial V_j} = (2V_i Y_{ij}) \sin(\theta_{ij}) + \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (15)
\]

The off-diagonal and diagonal elements of \( M \) are given by

\[
\frac{\partial Q_i}{\partial \delta_k} = -(V_i Y_{ik}) \cos(\delta_i - \delta_k - \theta_{ik}) , \quad i \neq k \quad (16)
\]

\[
\frac{\partial Q_i}{\partial \delta_k} = \sum_{k=1}^{n} (V_i Y_{ik}) \cos(\delta_i - \delta_k - \theta_{ik}) \quad (17)
\]

The off-diagonal and diagonal elements of \( L \) are given by

\[
\frac{\partial Q_i}{\partial \delta_k} = -\left( V_i Y_{ik} \sin(\delta_i - \delta_k - \theta_{ik}) \right) , \quad i \neq k \quad (18)
\]

\[
\frac{\partial Q_i}{\partial \delta_k} = -(2V_i Y_{ik}) \sin(\theta_{ij}) + \sum_{k=1}^{n} (V_i Y_{ik}) \sin(\delta_i - \delta_k - \theta_{ik}) \quad (19)
\]

It is seen from the elements of the Jacobian equations that there is no symmetry in the results. Multiplying and dividing by \( V \) the voltage magnitude increment \( \Delta V \) to bring symmetry in the result, we have,

\[
\Delta P = H \Delta \delta + (VN) \frac{\Delta V}{V} \quad (20)
\]

\[
\Delta Q = M \Delta \delta + (VL) \frac{\Delta V}{V} \quad (21)
\]

Let \( VN = N^t \) and \( VL = L^t \), we can write,

\[
\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (22)
\]

In this case it will be seen that \( H_{ik} = L_{ik} \) and \( N_{ik} = -M_{ik} \)

The property of symmetry of elements reduces the computer time and storage.

### 3.3 CONTINUATION POWER FLOW

The continuation power flow method is a mathematical path methodology used to solve systems of non-linear equations. Using the continuation method, a solution branch around the turning point can be tracked without difficulties. It has been used for studies with approximations of the critical point in power systems. The Continuation Power Flow (CPF) captures this path-following feature by means of a predictor-corrector scheme which adopts a locally parameterized continuation technique to trace the PF solution paths. As shown in Figure 2, it starts from a known solution and uses a tangent predictor to estimate a subsequent solution which corresponds to a different value of the load parameter \( \lambda \). Then, using the Newton-Raphson technique, the estimation value is corrected. For the parameterization, the local technique is used for identifying each point along the solution curve and makes part in avoiding singularity in the Jacobian [10].

**Figure 2. Predictor-corrector scheme used in the continuation power flow [10].**

This method will be used to ascertain the amount of load the Network can still take without causing a collapse and the behavior of the Network at the collapse point. To apply a local parameterization, the power flow equation is reformulated including a load parameter \( \lambda \). The load is considered using a constant load model. In the new equation formulated, the load parameter varies in the range of 0 to \( \lambda_{critical} \), where \( \lambda=0 \) corresponds to the base care and \( \lambda=\lambda_{critical} \) corresponds to the critical load. In general, the new equations form for each bus i are shown in equations 23 and 24

\[
\Delta P_i = P_{g_{i}(\lambda)} - P_{i}(\lambda) - P_{f_i} = 0 \quad (23)
\]

\[
\Delta Q_i = Q_{g_{i}(\lambda)} - Q_{i}(\lambda) - Q_{f_i} = 0 \quad (24)
\]

Where \( i, j, t \) denotes the load, generation and injection for each bus. The new network will be subjected to Newton-Raphson power flow analysis until it gets to the critical load.
3.4. Small signal stability analysis

Eigen value analysis will be considered for the small signal stability analysis. This analysis will investigate the weakest bus of the Network to ascertain the bus which should be given more attention. This method will also be used to place the FACTS devices for proper functioning of the Network. Modal analysis can predict voltage collapse in complex power Network which involves mainly the computing of the smallest eigenvalue and associated eigenvectors of the reduced Jacobian matrix obtained from load flow solution. Eigenvalues comprises of modes of voltage and reactive power changes which provides relative measure of proximity to voltage instability [5]. It can also be used to predict the weakest bus by determining the participating factor. The reduced Jacobian matrix $J_R$

$$J_R = \frac{\partial Q}{\partial V}$$  \hspace{1cm} (25)

The reduced jacobian matrix represents a linearized relationship between the increment changes in bus voltage ($\Delta V$) and the changes in reactive power ($\Delta Q$). Reduced Jacobian eigenvalues and eigenvectors are used for voltage instability characteristics analysis. When all the eigenvalues are positive, it can be said that the system is stable, but for a dynamic system which we are interested in, when the real parts are positive, the system can be said to be stable. A system can be considered unstable when at least one of the real parts is negative. It is not necessary determining all the $J_R$ of a Network, but the lowest $J_R$ can be considered as the bus which is prone to instability. It can be assumed that other buses are strong enough mode. Once the minimum eigenvalue have been found, the highest participation factor value can be determined which can be seen as the weakest bus [2].

3.5 UNIFIED POWER FLOW CONTROLLER (UPFC)

UPFC is the most flexible multi-functional FACTs device which is a new generation of FACTs devices. The UPFC is one of the most versatile devices. In UPFC, the transmitted power can be controlled by changing three parameters of power transmission line namely transmission magnitude voltage, impedance and phase angle. See Figure 3, the 52 bus network with UPFC FACTS device. The UPFC consists of two voltage source converters; series and shunt converter, which are connected to each other with a common dc link. Shunt converter (converter 1) or STATCOM is used to provide reactive power to the ac system, besides that, it will provide the dc power required for both inverters, while series converter (converter 2) or Static Synchronous Series Compensator (SSSC) is used to add controlled voltage magnitude line as shown in Figure 4. Each of the branches consists of a transformer and power electronic converter. These two voltage source converters shared a common dc capacitor [8]. UPFC tries to address the limitation of STATCOM and SSSC.

![Figure 3. The 52 bus network with UPFC FACTS device](http://ijesc.org/)

3.6. Simulation tool and method

The analysis was done using MATLAB 7.9 Power System Analysis Toolbox (PSAT). The simulation was done on the Normal Nigeria network and using UPFC as shown in Figure 3 on the three weakest Buses. The load flow analysis was first done on the normal network to reveal the state of the system before the inclusion of the FACTS device. The Eigen value analysis was then done to reveal the weakest bus before the inclusion of the UPFC in the position of the weakest Buses.

4.0 RESULTS AND DISCUSSION

The results for 52 bus system were gotten as follows; (i) without using FACTS device and (ii) with only one UPFC, two UPFC, and three UPFC FACTS device at different locations of the 52 bus network. Their line losses, voltage violations, real Jacobian and maximum loading result were all gotten and compared for the best number of FACTS device to be considered for the 52 Bus systems.

![Figure 4. Configuration of UPFC [8].](http://ijesc.org/)

![Figure 5. Voltage profile for 52 Bus Network without FACTS device.](http://ijesc.org/)

![Figure 6. Network visualization of 52 bus network without FACTS device.](http://ijesc.org/)
The result above in Figure 5 and Figure 6 shows the voltage profile and the Network visualization of the system. There is no result for CPF due to the inability of the Network to accept more load into the Network. Considering the Eigen value analysis, as seen in Table 1 and Figure 7, shows that the system is unstable and the most affected bus is Bus 45. Considering the participation factor of Bus 45, shows that the Buses which contributed more to the instability are Buses 45, 11 and 6. This shows that the UPFC device will be attached to Buses 45, 11 and 6 respectively or line closer to the Buses.

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The comparison was done considering power flow results and the CPF results as shown in Table 2. Addition of one and two UPFC devices to the Network was able to improve the real and reactive powers losses of the Network, but no improvement on load addition since no result was seen for the CPF. The introduction of three UPFC devices at the weakest Buses shows a significant improvement on the voltage violation, as no voltage was violated. At the collapse point also, no voltage was also violated for the three FACTS devices introduced. The system status shows that the system attained stability when UPFC devices were introduced. Comparing the normal real power losses, three UPFC will be more preferred for the proposed Network with 0.25032pu real power loss. Comparing the number of UPFC devices maximum loading results, it is clear that addition of three UPFC gave the best result of 1.1002pu (3.9%) as it can accept more load into the Network and has minimal real and reactive power losses at the collapse point.

5.0 CONCLUSION

There is every tendency that Nigeria 330kV network might tend to collapse if ways or approaches are not developed to optimize the power system network due to daily increase in load demand. The problem of reactive power imbalance which is the major source of voltage instability can be countered using FACTS devices which have the capability to inject or absorb reactive power. FACTS devices can be used to optimize the Nigerian network, especially on the voltage profile and line losses. The Nigerian present Network can be optimized to attain stability and also accept more load if FACTS devices are introduced. There is significant improvement in the voltage profile, real and reactive power losses on the introduction of UPFC FACTS device. The main advantage of this work is that it considers the introduction of three same FACTS devices at three different locations of the Network as compared to only one or two FACTS device could not bring significant improvement in the Network. These FACTS device were located at the point of the weakest Bus in

Table 2. Comparison of location of different numbers of UPFC FACTS device on the 52 bus network

<table>
<thead>
<tr>
<th>FACTS Device</th>
<th>Voltage Violation</th>
<th>Real Power Loss (pu)</th>
<th>Reactive Power Loss (pu)</th>
<th>CPF Voltage</th>
<th>CPF Real Power Loss (pu)</th>
<th>CPF Reactive Power Loss (pu)</th>
<th>Maximum Loading Capability (pu)</th>
<th>System Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without FACTS device</td>
<td>1</td>
<td>0.676</td>
<td>5.2435</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Unstable</td>
</tr>
<tr>
<td>With UPFC at Bus 6</td>
<td>1</td>
<td>0.4963</td>
<td>4.6471</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Unstable</td>
</tr>
<tr>
<td>With UPFC at Buses 6 and 11</td>
<td>1</td>
<td>0.3912</td>
<td>3.7241</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Unstable</td>
</tr>
<tr>
<td>With UPFC at Buses 6, 11 and 45</td>
<td>0</td>
<td>0.25032</td>
<td>4.56332</td>
<td>0</td>
<td>0.35542</td>
<td>4.98541</td>
<td>1.1002</td>
<td>Stable</td>
</tr>
</tbody>
</table>

UPFC were also introduced in the network at Buses 45, 11 and 6 to study if it will further improve the behavior of the network as compared to when FACTS device was not attached. No result was found for CPF for the placement of FACTS at Bus 6 and Buses 6 and 11. A progressive improvement was seen in the real and reactive power losses of 0.4963pu and 0.3912pu for real power and 4.6471pu and 3.7241pu for reactive power for placement of FACTS at Bus 6, and, Buses 6 and 11 respectively. No Bus was violated as shown in Figure 10 and the different voltage ranges on the Network are shown in the Network visualization in Figure 13. The CPF result shows that only 1.0335pu power can still be loaded into the network without causing a collapse and no Bus was violated at the collapse point as seen in Figure 11 and 12.

The analysis done on 52 Bus Network above was compared using Table 2 below with the voltage violations, real and reactive power losses, maximum loading and system status.

Figure 12. V-P curve for 52 Bus Network using UPFC for Buses 6, 11 and 45

Figure 13. Network visualization of 52 bus system using UPFC for Buses 6, 11 and 45

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the network, and it was confirmed that this aided in correcting the violated Buses, optimizing and attaining stability of the Network, and was proven to make the most tremendous positive impact because it helped the network to accept more load up to 1.1002 p.u (3.9%) than other FACTS devices.

6.0. REFERENCES


