Power Loss Determination, Assessment and Enhancement of the Nigerian Power System Network

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Abstract

For sustainability to be recorded in the Nigeria power sector (NPS), there must be a well-integrated system that is not easily prone to failure and is readily available when called into action. The NPS has overtime suffered from degraded infrastructure, policy paralysis to mention but few. However, if the needful is done with respect to identifying weak links in the network and a corresponding fast action in clearing failures along the line(s) then, some remarkable achievements could be recorded. This paper, therefore, carried out power flow analysis using the Newton Raphson Algorithm on the Electrical Transient Analyser Program (ETAP) version 12.6 on the NPS network using Maryland transmission station (MTS), Lagos, Nigeria as a case study. The choice of the location was as a result of the sensitivity of Lagos State in the economic activities of Nigeria. Results from the load flow indicated several voltage violations at load1 bus, load3 bus and load5 bus with magnitudes of 94.51, 94.91 and 94.79 % respectively. Consequently, transformers designated as T2A and T3A were said to have the highest and lowest branch losses of 150.0kW and 18.2kW respectively. Compensation of the losses along the line was carried out using optimal capacitor placement (OCP) subjected to constraints on the ETAP environment. The results from the OCP showed that it optimally sized and placed four capacitor banks on four of the candidate buses, which include load1 bus, load2 bus, load3 bus and load5 bus. An improvement of 2.26%, 1.12%, 1.93%, 1.12% and 2.006% were recorded for load1 bus, load2 bus, load3 bus, load4 bus and load5 bus respectively.

Keywords

ETAP; Load bus; Maryland transmission station; Newton Raphson; Power flow; Simulation.

1. Introduction

The prevalent instability in the Nigerian power sector (NPS) has overtime affected its growth economically. The failures emanated from the NPS may either be technical or non-technical in nature. To this end, the operators of the system are seldom forced to operate the system under stressed conditions in order to meet up with the demand of the customers. Omorugiuwa & Ogujor (2012) presented the state of power generation as well as the integrated system that is not easily prone to failure and is readily available when called into action. The NPS has overtime suffered from degraded infrastructure, policy paralysis to mention but few. However, if the needful is done with respect to identifying weak links in the network and a corresponding fast action in clearing failures along the line(s) then, some remarkable achievements could be recorded. This paper, therefore, carried out power flow analysis using the Newton Raphson Algorithm on the Electrical Transient Analyser Program (ETAP) version 12.6 on the NPS network using Maryland transmission station (MTS), Lagos, Nigeria as a case study. The choice of the location was as a result of the sensitivity of Lagos State in the economic activities of Nigeria. Results from the load flow indicated several voltage violations at load1 bus, load3 bus and load5 bus with magnitudes of 94.51, 94.91 and 94.79 % respectively. Consequently, transformers designated as T2A and T3A were said to have the highest and lowest branch losses of 150.0kW and 18.2kW respectively. Compensation of the losses along the line was carried out using optimal capacitor placement (OCP) subjected to constraints on the ETAP environment. The results from the OCP showed that it optimally sized and placed four capacitor banks on four of the candidate buses, which include load1 bus, load2 bus, load3 bus and load5 bus. An improvement of 2.26%, 1.12%, 1.93%, 1.12% and 2.006% were recorded for load1 bus, load2 bus, load3 bus, load4 bus and load5 bus respectively.

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where the effect of power outage is felt greatly; perhaps, suffers from neglect from the appropriate authority. Due to the sensitivity of the distribution arm of the NPS, it would have been expected that there is an up-to-date maintenance, well integrated Supervisory Control and Data Acquisition (SCADA) System. Nevertheless, the reverse is the case.

This paper is aimed at carrying power flow study on the Maryland transmission station in order to investigate the system performance using the ETAP software.

2. Methodology

2.1 Load Flow Analysis

Load flow analysis using software is accurate and gives highly reliable results. In this paper, an effective use of Electrical Transient Analyser Program (ETAP) software on the load flow analysis of the 132/33/11 kV Maryland sub-transmission station was implemented. The Maryland power station is located at Mushin, Nigeria (Lat. 6°34′16″N, Long. 3°22′18″E). The single line diagram (SLD) of the Maryland sub-transmission power network is shown in Figure 1. The network draws power from the grid at a voltage level of 132kV, which is being stepped down to 33kV using three power transformers and similarly to 11 kV as well. The power network consists of two 33kV feeders and three (3) 11kV feeders.

The nomenclature used in the load flow analysis is: $V_i$ - $i^{th}$ bus voltage; $Y_{ij}$ - admittance of line between $i^{th}$ and $j^{th}$ bus; $Y_{ii}$ - self admittance of line connected to $i^{th}$ bus; $P_i$ - real power injected into $i^{th}$ bus; $Q_i$ - reactive power injected into $i^{th}$ bus; $I_i$ - bus current at $i^{th}$ bus; $\theta_{ij}$ - angle of $Y_{ij}$ element of $Y_{bus}$; $\delta_i$ - voltage angle of $i^{th}$ bus; $i, j$ - integer (0 to n); and n - no. of buses (Archita et al., 2016). Each transmission line has been admittance between the bus and the ground. If there is no transmission line between $i^{th}$ and $j^{th}$ bus, then the corresponding element of the bus admittance matrix $Y_{ij}$ is 0.

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_n \\
\end{bmatrix}
= 
\begin{bmatrix}
Y_{11} & \cdots & Y_{1n} \\
\vdots & \ddots & \vdots \\
Y_{n1} & \cdots & Y_{nn} \\
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
\vdots \\
V_n \\
\end{bmatrix}
\]

\[(1)\]

\[
I_{bus} = Y_{bus} \cdot V_{bus}
\]

\[(2)\]
Power Loss Determination, Assessment and Enhancement of the Nigerian Power System Network

Where \( Y_{ij} \) is the admittance of the line between \( i \)th and \( j \)th bus, \( V_i \) is the \( i \)th bus voltage and \( I_i \) is the bus current at \( i \)th bus.

In this paper, the Newton Raphson method was adopted because it converges faster than Gauss Seidel (David et al., 1984) and suitable for large systems. Generally, the Newton Raphson (NR) equation in a compact form is given as follows:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
Y_{11} & Y_{12} & Y_{13} \\
Y_{21} & Y_{22} & Y_{23} \\
Y_{31} & Y_{32} & Y_{33}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix}
\]

(3)

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 \\
-1 & 0 & 0 \\
1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \delta \\
\Delta V
\end{bmatrix}
\]

(4)

Where, \( \Delta P, \Delta Q \) are mismatch vectors.

\( P_i \) (scheduled) – \( P_i \) calculated = \( \Delta P_i \)

(5)

\( Q_i \) (scheduled) – \( Q_i \) calculated = \( \Delta Q_i \)

(6)

The Maryland sub-transmission power network was developed using ETAP software (Version 12.6). The development of the power network was achieved with the aid of the SLD (Figure 1) and the actual data of the network elements obtained from the station. The Maryland power network was modelled in ETAP using the ETAP “Edit Mode” environment. The “Edit Mode” contains several components (AC and DC), which are utilised in the system development process. These components represent the actual components obtained in real life scenario. The required components are dragged unto the model space, positioned and connected appropriately. The components are edited with the actual data obtained from the Maryland sub-transmission station as shown in Table 1. The developed ETAP model of the Maryland power station is shown in Figure 2.

The load flow analysis was performed by switching from the ETAP “Edit Mode” to the ETAP “Run Mode”. The interface of the “Run Mode” contains the necessary tools needed for performing load flow analysis. Before performing the load flow analysis, there are several settings, which are needed to be done for an effective simulation. Some of the settings were achieved through the “Load Flow Study Case” editor. Through this study case editor, the required load flow analysis method was set. ETAP performs load flow analysis using four methods. These methods are the Adaptive Newton-Raphson (ANR), Newton-Raphson (NR), Fast-Decoupled (FD) and Accelerated Gauss-Seidel (AGS).

Each of these methods possesses different convergent characteristics. Considering the Newton-Raphson and Adaptive Newton-Raphson methods, a few Gauss-Seidel iterations were made first to establish a set of good initial values for the bus voltages since the convergence of the Newton-Raphson method is highly dependent on the initial bus voltages. In this paper, the Newton-Rapson load flow method was applied, by utilising the NR algorithm. The simulation of the developed model is as shown in Figure 3.

![Figure 2. ETAP model of the Maryland substation](image-url)
2.2 Bus Voltage Profile Enhancement

The objective function of the load flow is defined as follows:

\[ \text{Objective function}_{\text{min}} = \sum_{i=1}^{N_{\text{bus}}} (x_i C_0 i + Q_i C_1 i + B_i C_2 i T_i + C_2 \sum_{l=1}^{N_{\text{load}}} T_l P_l) \]  
\[ \text{min} \]  
(5)

where, \( N_{\text{bus}} \) is the number of bus candidates, \( x_i \) is either zero (indicating no capacitor installed at bus \( i \)) or one (indicating the installation of capacitor at bus \( i \)), the installation cost ($), \( C_0 i \) is the installation cost ($), \( C_1 i \) is the per kVar cost of capacitor banks ($/kVar), \( Q_i \) is the size of the capacitor bank (kVar), \( B_i \) is the number of capacitor banks, \( C_2 i \) is the operating cost of capacitor banks per year ($/y), \( C_2 \) is the cost per kWh loss ($/kWh), \( T \) is the planning period (y), \( I_l \) is the load levels: maximum, average and minimum (%), \( T_l \) is the time duration of the load level (h), and \( P_l \) is the total system loss at load level \( I_l \).

The main constraints for optimal capacitor placement are to meet the load flow constraints. In addition, all voltage magnitude of load (PQ) buses should be within the allowable limit. The constraint considered for all load (PQ) buses in this paper is given by the equation:

\[ F(x,u) = 0 \]
\[ V_{\text{min}} \leq V \leq V_{\text{max}} \]  
(6)

Where, \( V_{\text{min}} \) is the minimum voltage limit (= 95%) and \( V_{\text{max}} \) is the maximum voltage limit (= 105%) chosen in this paper.

2.3 Capacitor Sizing and Placement for Losses Reduction

The optimal location of capacitors is modelled using the Loss sensitivity factor (LSF) according to Vijay et al. (2016), which identified buses with voltage violation that requires compensation. The real power loss in the network of a given branch \( m \) is given by the equation:

\[ P_{\text{loss}} = \frac{r_m (P_m^2 + Q_m^2)}{V_m^2} \]  
(7)

where, \( r_m \) is the resistance (\( \Omega \)) in branch \( m \), \( r_m \) is the voltage profile (V) of bus \( m \), and \( P_m \) (kW) and \( Q_m \) (kVAR) are the real and reactive power drawn from bus \( m \) respectively.

The loss sensitivity factor (LSF) of the network branches and the net system loss of the real power (TPloss) in the network can be computed respectively, using the following equations:

\[ \text{LSF} = \frac{\partial P_{\text{loss}}}{\partial Q_{\text{loss}}} = \frac{2xQ_m r_m}{V_m^2} \]  
(8)

\[ TP_{\text{loss}} = \sum_{m=1}^{n_{\text{br}}} W_m (P_m^2 + Q_m^2) \]  
(9)

Given that:

\[ W_m = \frac{r_m}{V_m} \]  
(10)

Where, \( n_{\text{br}} \) represents the number of branches and \( m \) represents buses at the receiving end of each branch.

The net real power loss after optimal installation of capacitors in the network is deduced using the following equation:
\[ TP_{loss}^{cap} = \sum_{m \in B_{cap}} W_m \left[ P_m^2 + \left( Q_m - \sum_{k=1}^{z} B_{mk} Q_k^{cap} \right)^2 \right] + \sum_{m \not\in B_{cap}} W_m \left[ P_m^2 + Q_m^2 \right]. \] (11)

Where, \( m \in B_{cap} \) depicts that branch \( m \) is for \( B_{cap} \), \( m \not\in B_{cap} \) depicts that branch \( m \) is not for \( B_{cap} \), \( z \) represents the number of capacitors, \( B_{mk} \) represents a binary matrix \((B_{cap} \times z)\) whose elements can be deduced as follows:

\[ B_{mk} = \begin{cases} 
\text{reactive power (Q_k)} & \text{at k}\text{th node flows through m} \\
0 & \text{otherwise}
\end{cases} \] (12)

The net real power loss saved after optimal installation of capacitors in the network is computed using the equation:

\[ \Delta TP_{loss} = TP_{loss} - TP_{loss}^{cap} = \sum_{m \in B_{cap}} W_m \left[ 2Q_m \sum_{k=1}^{z} B_{mk} Q_k^{cap} - \left( \sum_{k=1}^{z} B_{mk} Q_k^{cap} \right)^2 \right] \] (13)

Differentiating (13) with respect to \( Q_i^{cap} \) at bus \( i \)

\[ \frac{\partial \Delta TP_{loss}}{\partial Q_i^{cap}} = 2 \sum_{m \in B_{cap}} B_{mi} W_m \left( Q_m - \sum_{k=1}^{z} B_{mk} Q_k^{cap} \right) \] (14)

The net maximum real power loss saved at first differentiation equals zero, i.e.,

\[ \frac{\partial \Delta TP_{loss}}{\partial Q_i^{cap}} \bigg|_{Q_k^{cap} = Q_k^{opt, cap}} = 0 \] (15)

A matrix representation of the sizes of capacitors at multiple locations in a network is given as follows:

\[ [Q_{k, opt}^{cap}] = [X_1, 1, Z_2, 1] \] (17)

\[ Q_{1, opt}^{cap} = X_1, 1, Q_{2, opt}^{cap} = X_2, 1, \ldots, Q_{z, opt}^{cap} = X_z, 1 \] (18)

Where,

\[ [X_{g, h}] = \sum_{m \in B_{cap}} B_{mg} W_m \] \( g \in B_{cap} \) \( h \in B_{cap} \) (19)

\[ [Y_h] = \sum_{m \in B_{cap}} B_{mh} W_m Q_m \] (20)

The simulated ETAP model with the capacitor banks installed is shown in Figure 4.

**Figure 4.** Simulated ETAP model of the Maryland network with installed capacitor banks after compensation
3. Results and Discussion

Table 1 and Table 2 show the load flow analysis of the developed model for Maryland network before and after compensation respectively. Table 3 compares the branch losses of the developed model of the Maryland network before and after compensation.

Table 1. Load flow analysis of developed model for Maryland network before compensation

| Bus | Voltage | Generation | Load | Load Flow |
|-----|---------|------------|------|-----------|
| ID  | kV      | % Mag. | Ang. | MW MVAR | MW MVAR | Amp | % PF |
| Bus 1 | 132    | 100.000 | 0.0 | 46.583 | 33.727 | 0   | 0    |
| Bus 2 | 23.135 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 3 | 11.667 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 4 | 11.667 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 5 | 11.667 | 0.0 | 0   | 0   | 0   | 0   | 0    |

Table 2. Load flow analysis of developed model for Maryland network after compensation

| Bus | Voltage | Generation | Load | Load Flow |
|-----|---------|------------|------|-----------|
| ID  | kV      | % Mag. | Ang. | MW MVAR | MW MVAR | Amp | % PF |
| Bus 1 | 132    | 100.000 | 0.0 | 48.086 | 18.850 | 0   | 0    |
| Bus 2 | 23.935 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 3 | 12.039 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 4 | 11.667 | 0.0 | 0   | 0   | 0   | 0   | 0    |
| Bus 5 | 11.667 | 0.0 | 0   | 0   | 0   | 0   | 0    |

Table 3. Branch losses comparison

| Branch | Losses |
|--------|--------|
| Before Compensation | After Compensation |
| Load 1 | 14.500 | 14.500 |
| Load 2 | 14.500 | 14.500 |
| Load 3 | 14.500 | 14.500 |
| Load 4 | 14.500 | 14.500 |
| Load 5 | 14.500 | 14.500 |
Table 3. Comparison of branch losses of developed model for Maryland network before and after compensation

| CKT/Branch | From-To Bus Flow | To-From Bus Flow | Losses | % Bus Voltage Drop in | % VA Drop in Vavg |
|------------|-----------------|-----------------|--------|-----------------------|------------------|
| ID         | MW   | MVAR | kW    | kVAR     | From | To    |
| T1         | 11.772 | 8.255 | -33.3 | 619.3 | 1000 | 97.4 |
| T2         | 23.135 | 17.080 | -36.4 | 1239.9 | 1000 | 97.4 |
| T3         | 11.676 | 8.391 | 26.1 | 619.7 | 1000 | 97.4 |
| T1A        | 7.167 | 5.775 | 22.4 | 416.2 | 97.4 | 94.5 |
| T2A        | 8.737 | 2.711 | 150.0 | 370.4 | 97.4 | 94.9 |
| T3A        | 6.488 | 5.191 | 18.2 | 239.2 | 97.4 | 94.8 |

Branch losses before compensation

| CKT/Branch | From-To Bus Flow | To-From Bus Flow | Losses | % Bus Voltage Drop in | % VA Drop in Vavg |
|------------|-----------------|-----------------|--------|-----------------------|------------------|
| ID         | MW   | MVAR | kW    | kVAR     | From | To    |
| T1         | 12.092 | 4.351 | -26.9 | 499.5 | 1000 | 98.5 |
| T2         | 23.955 | 9.649 | 29.3 | 1000.0 | 1000 | 98.5 |
| T3         | 12.039 | 4.670 | 21.1 | 499.8 | 1000 | 98.5 |
| T1A        | 7.569 | 3.417 | 17.6 | 328.8 | 98.5 | 96.8 |
| T2A        | 8.089 | 3.315 | 149.3 | 567.8 | 98.5 | 96.8 |
| T3A        | 6.761 | 3.366 | 14.7 | 273.9 | 98.5 | 96.8 |

Branch losses after compensation

The load flow results presented in Table 1 shows voltage violations in percentages at Load1 bus, Load3 bus and Load5 bus with magnitudes of 94.506%, 94.908% and 94.792% respectively. The normal range of bus voltages assumed is 95-105%. Load1 bus has the highest voltage violation.

In order to restore the Maryland network to normalcy, compensation of the losses was carried out, which in turn enhances the voltage profile of the buses as shown in Table 2. The compensation in this case was achieved through the utilisation of the Optimal Capacitor Placement (OCP) module of the ETAP software. Five buses (Load1 bus – load5 bus) were selected as candidate buses for capacitor placement. After simulating the network using the OCP, it optimally sized and placed capacitor banks on the candidate buses. The compensation was achieved through optimal sizing and placement of capacitor banks at affected buses. This compensation leads to an overall improvement of other buses in the network.

Table 3 shows a summary of the branch losses associated with the network before and after compensation. It can be inferred from the result that before compensation, transformer T2A and T3A has the highest and lowest branch losses of 150.0 kW and 18.2 kW respectively. In addition, an overall system losses of 286.4 kW and 3604.6 kVAR were experienced by the network. Conversely, the overall system losses after compensation significantly reduced from 286.4 kW to 258.8 kW and 3604.6 kVAR to 2968.7 kVAR, which corresponds to 9.64% and 17.64% enhancement respectively. The percentage improvement of the respective bus voltages is shown in Table 4.

4. Conclusion

In this paper, the load flow analysis of Maryland transmission station using the Electrical Transient Analyser Program (ETAP) software was carried out. The bus voltage magnitudes and phase angles including the power flow and losses of the substation were obtained. Abnormal operating conditions were observed from the output results obtained. The load flow simulation result showed that most of the buses in the network violated the voltage limits in addition to some losses experienced.

Performing load flow analysis using ETAP software is an excellent tool employed for system planning. A lot of operating procedures can be analysed such as outage of equipment. The analysis is also useful in determining the system operating state under contingency conditions to ascertain whether the equipment involved are operating within the specified limit. It can also be used to identify the need for additional generation, capacitive or inductive VAR support, or placement of capacitors or reactors in view of restoring the normal operating state of the system.
Conflict of Interests
The authors declare that there is no conflict of interests regarding the publication of this paper.

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