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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.

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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 on-going National Integrated Power Project (NIPP) projects targeted at improving and creating sustainability in the system. But as time passes on, little or no improvements have been recorded. In the assertion of Okundamiya *et al.* (2009) poor voltage profile were recorded at the investigative injection sub-stations. Patrick *et al.* (2013) and Sunday & Friday (2010) observed that the southern part of Nigeria was characterised with over voltages while the western part was characterised by network congestion.

A study carried out by Airoboman *et al.* (2015) showed that the Benin bus is the most sensitive in the NPS and as such, needs to be upgraded and compensated. Various studies have been done on the review of the application of controllers (Amaize *et al.* 2017; Okakwu *et al.* 2017) in the NPS as well as on load flow study (Agbontaen & Ike, 2017; Ogbuefi & Madueme, 2015; Onohaebi & Igbinovia, 2008; Onojo *et al.* 2013). However, these studies were limited to the transmission 330kV lines only. The distribution arm of the NPS, the point

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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: Vi - i^{th} bus voltage; Vj - j^{th} bus voltage; Yij - admittance of line between i^{th} and j^{th} bus; Yii - self admittance of line connected to i^{th} bus; Pi - real power injected into i^{th} bus; Qi - reactive power injected into i^{th} bus; Ii - bus current at i^{th} bus; θ_{ij}- angle of Yij element of Y_{bus}; δ_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 Yij is 0.

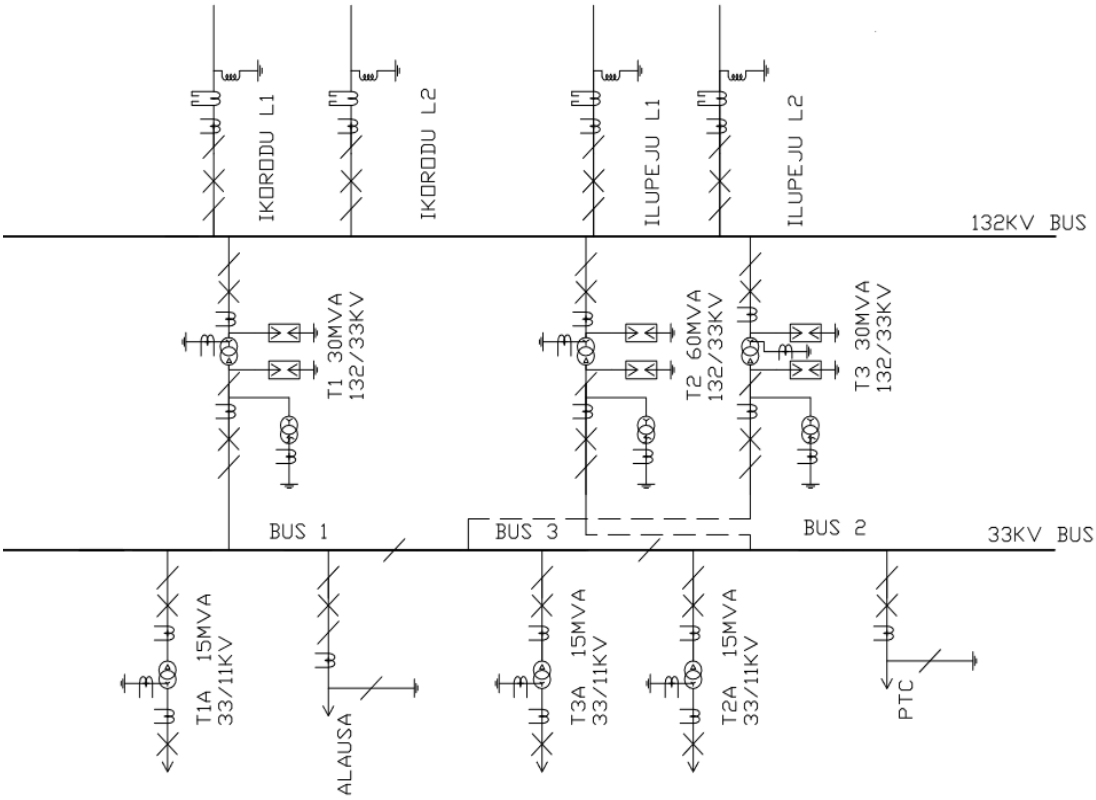

Figure 1. Single line diagram of the Maryland sub-transmission power network

$$\begin{bmatrix} I_1 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{1i} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} \quad (1)$$

$$I_{bus} = Y_{bus} * V_{bus} \quad (2)$$

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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:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} j1 & j2 \\ j3 & j4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [j] \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{4}$$

Where, ΔP, ΔQ are mismatch vectors.

$$P_i \text{ (scheduled)} - P_i^r \text{ calculated} = \Delta P_i^r \tag{5}$$

$$Q_i \text{ (scheduled)} - Q_i^r \text{ calculated} = \Delta Q_i^r \tag{6}$$

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 differerent 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.

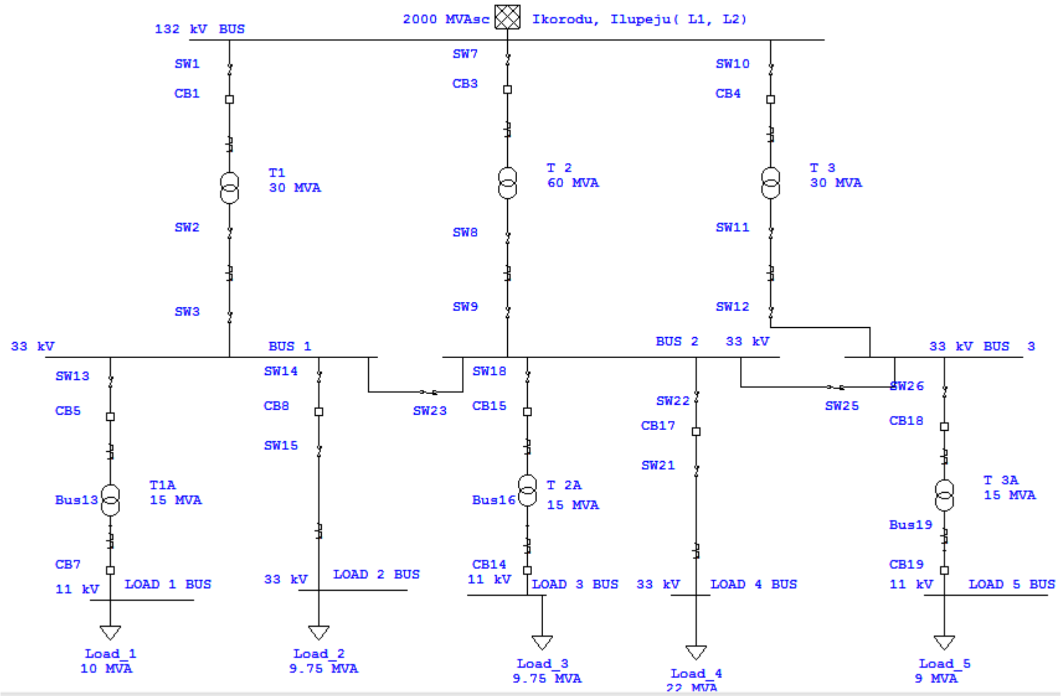

Figure 2. ETAP model of the Maryland substation

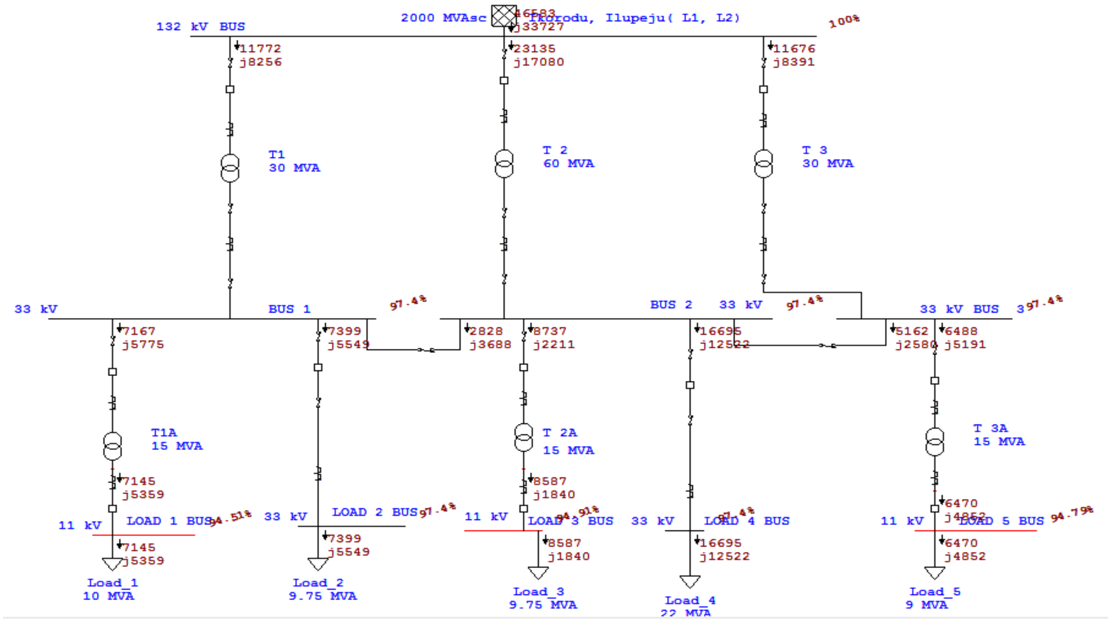

Figure 3. Simulated model of the Maryland substation

2.2 *Bus Voltage Profile Enhancement*

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

$$\text{Objective function}_{min} = \sum_{i=1}^{N_{bus}} (x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T) + C_2 \sum_{l=1}^{N_{load}} T_l P_L{}^l \quad (5)$$

where, N_{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_{oi} is the installation cost (\$), C_{1i} is the per kVar cost of capacitor banks (\$/kVar), Q_{ci} is the size of the capacitor bank (kVar), B_i is the number of capacitor banks, C_{2i} 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), 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 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:

Load Flow: $F(x, u) = 0$

$$V_{min} \leq V \leq V_{max} \quad (6)$$

Where, V_{min} is the minimum voltage limit (= 95%) and V_{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:

$$P_{loss} = \frac{r_m (P_m{}^2 + Q_m{}^2)}{V_m{}^2}, \quad (7)$$

where, r_m is the resistance (Ω) in branch m, v_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 (TP_{loss}) in the network can be computed respectively, using the following equations:

$$LSF = \frac{\partial P_{loss}}{\partial Q_{loss}} = \frac{2 \times Q_m \times r_m}{V_m{}^2}. \quad (8)$$

$$TP_{loss} = \sum_{m=1}^{nbr} W_m (P_m{}^2 + Q_m{}^2). \quad (9)$$

Given that:

$$W_m = \frac{r_m}{V_m{}^2}, \quad (10)$$

Where, nbr 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:

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$$TP_{loss}{}^{cap} = \sum_{m\in Bcap} W_m \left[P_m{}^2 + (Q_m - \sum_{k=1}^{z} B_{mk} Q_k{}^{cap})^2\right] + \sum_{m\notin Bcap} W_m \left[P_m{}^2 + Q_m{}^2\right]. \quad (11)$$

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

$$B_{mk} = \begin{cases} reactive\ power\ (Q_k{}^c)\ at\ k^{th}\ node\ flows\ through\ m \\ 0;\ otherwise \end{cases} \quad (12)$$

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

$$\triangle TP_{loss} = TP_{loss} - TP_{loss}{}^{cap} = \sum_{m\in Bcap} W_m [2Q_m \sum_{k=1}^{z} B_{mk} Q_k{}^{cap} - (\sum_{k=1}^{k} B_{mk} Q_k{}^{cap})^2] \quad (13)$$

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

$$\frac{\partial \Delta TP_{loss}}{\partial Q_i{}^{cap}} = 2\sum_{m\in Bcap} B_m W_m (Q_m - \sum_{k=1}^{k} B_{mk} Q_k{}^{cap}) \quad (14)$$

$i \in z$

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

$$\frac{\partial \Delta TP_{loss}}{\partial Q_i{}^{cap}} \Big|_{Q_k{}^{cap} = Q_{k,opt}{}^{cap}} \quad (15)$$

$$\sum_{m\in Bcap} B_{mi} W_m \sum_{k=1}^{k} B_{mk} Q_{k,opt}{}^{cap} = \sum_{m\in Bcap} B_{mi} W_m Q_m \quad (16)$$

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

$$[Q_{k,opt}{}^{cap}] = [X]^{-1}_{2\times 2}[Y]_{2\times 1} \quad (17)$$

$$\begin{bmatrix} Q_{1,opt}{}^{cap} \\ Q_{2,opt}{}^{cap} \\ \vdots \\ Q_{z,opt}{}^{cap} \end{bmatrix} = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,z} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,z} \\ \vdots & \vdots & \vdots & \vdots \\ X_{z,1} & X_{z,2} & \cdots & X_{z,z} \end{bmatrix} \quad (18)$$

Where,

$$[X_{g,h}] = \sum_{mcBcap} B_{mg} W_m B_{mh} \quad (19)$$

$$[Y_h] = \sum_{mcBcap} B_{mh} W_m Q_m \quad (20)$$

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

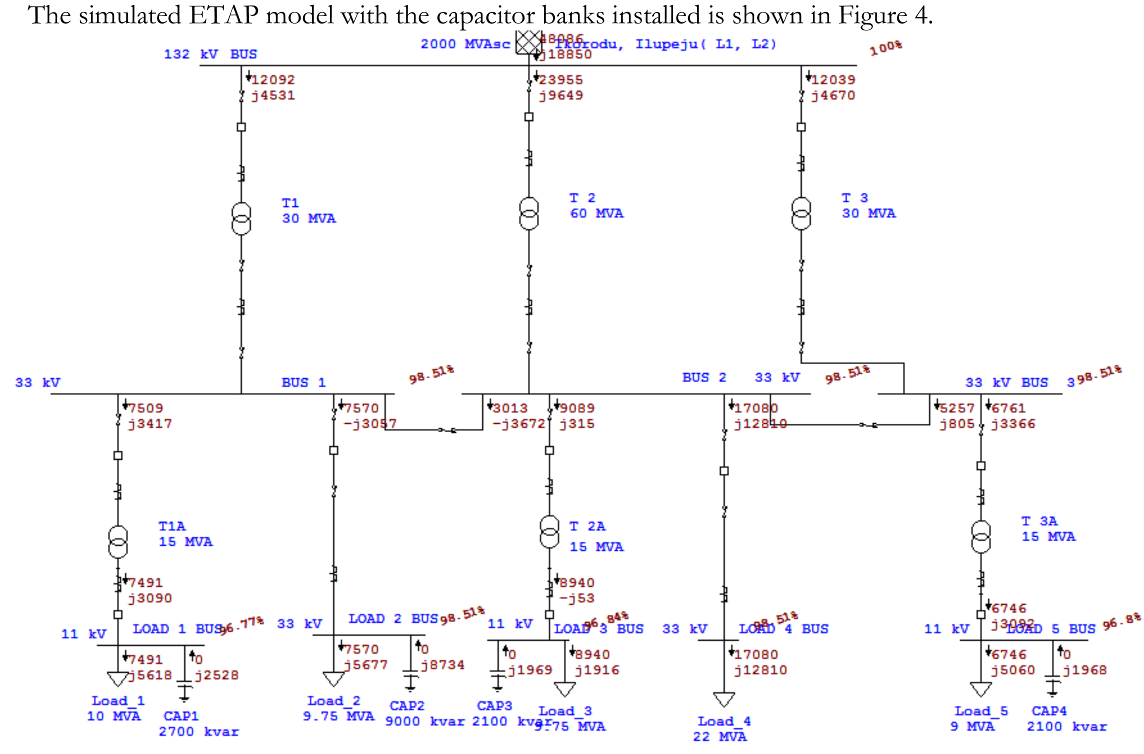

Figure 4. Simulated ETAP model of the Maryland network with installed capacitor banks after compensation

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	ID	MW	MVAR	Amp	% PF
Bus	132	100.000	0.0	46.583	33.727	0	0	Bus 1	11.772	8.256	62.9	81.9
								Bus 2	23.135	17.080	125.8	80.4
								Bus 3	11.676	8.391	62.9	81.2
Bus 1	33	97.396	-2.0	0	0	0	0	Bus	-11.739	-7.636	251.6	83.8
								Bus 13	7.167	5.775	165.3	77.9
								Load2 Bus	7.399	5.549	166.1	80.0
								Bus 2	-2.828	-3.688	83.5	60.8
Bus 2	33	97.396	-2.0	0	0	0	0	Bus	-23.098	-15.841	503.1	82.5
								Bus 16	8.737	2.211	161.9	96.9
								Load4 Bus	16.695	12.522	374.9	80.0
								Bus 1	2.828	3.688	83.5	60.8
								Bus 3	-5.162	-2.580	103.7	89.5
Bus 3	33	97.396	-2.0	0	0	0	0	Bus	-11.650	-7.771	251.6	83.2
								Bus 19	6.488	5.191	149.3	78.1
								Bus 2	5.162	2.580	103.7	89.5
Bus 13	11	94.506	-4.0	0	0	0	0	Bus 1	-7.145	-5.359	496.0	80.0
								Load1 Bus	7.145	5.359	496.0	80.0
Bus 16	11	94.908	-4.1	0	0	0	0	Bus 2	-8.587	-1.840	485.7	97.8
								Load 3 Bus	8.587	1.840	485.7	97.8
Bus 19	11	94.792	-3.8	0	0	0	0	Bus 3	-6.470	-4.852	447.8	80.0
								Load5 Bus	6.470	4.852	447.8	80.0
Load1 Bus	11	**94.506**	-4.0	0	0	7.145	5.359	Bus 13	-7.145	-5.359	496.0	80.0
Load2 Bus	33	97.396	-2.0	0	0	7.399	5.549	Bus 1	-7.399	-5.549	166.1	80.0
Load3 Bus	11	**94.908**	-4.1	0	0	8.587	1.840	Bus 16	-8.587	-1.840	485.7	97.8
Load4 Bus	33	97.396	-2.0	0	0	16.695	12.522	Bus 2	-16.695	-12.522	374.9	80.0
Load5 Bus	11	**94.792**	-3.8	0	0	6.470	4.852	Bus 19	-6.470	-4.852	447.8	80.0

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	ID	MW	MVAR	Amp	% PF
Bus	132	100.000	0.0	48.086	18.850	0	0	Bus 1	12.092	4.531	56.5	93.6
								Bus 2	23.955	9.649	113.0	92.8
								Bus 3	12.039	4.670	56.5	93.2
Bus 1	33	98.512	-2.1	0	0	0	0	Bus	-12.065	-4.031	225.9	94.8
								Bus13	7.509	3.417	146.5	91.0
								Load 2 Bus	7.570	-3.057	145.0	-92.7
								Bus 2	-3.013	3.672	84.4	-63.4
Bus 2	33	98.512	-2.1	0	0	0	0	Bus	-23.926	-8.649	451.8	94.0
								Bus16	9.089	0.315	161.5	99.9
								Load4 Bus	17.080	12.810	379.2	80.0
								Bus 1	3.013	-3.672	84.4	-63.4
								Bus 3	-5.257	-0.805	94.4	98.8
Bus 3	33	98.512	-2.1	0	0	0	0	Bus	-12.018	-4.170	225.9	94.5
								Bus19	6.761	3.366	134.1	89.5
								Bus 2	5.257	0.805	94.4	98.8
Bus 13	11	96.767	-4.1	0	0	0	0	Bus 1	-7.491	-3.090	439.5	92.4
								Load1 Bus	7.491	3.090	439.5	92.4
Bus 16	11	96.838	-4.4	0	0	0	0	Bus 2	-8.940	0.053	484.6	100.0
								Load3 Bus	8.940	-0.053	484.6	100.0
Bus 19	11	96.798	-3.9	0	0	0	0	Bus 3	-6.746	-3.092	402.4	90.9
								Load5 Bus	6.746	3.092	402.4	90.9
Load1 Bus	11	96.767	-4.1	0	0	7.491	3.090	Bus13	-7.491	-3.090	439.5	92.4
Load2 Bus	33	98.512	-2.1	0	0	7.570	-3.057	Bus 1	-7.570	3.057	145.0	-92.7
Load3 Bus	11	96.838	-4.4	0	0	8.940	-0.053	Bus16	-8.940	0.053	484.6	100.0
Load4 Bus	33	98.512	-2.1	0	0	17.080	12.810	Bus 2	-17.080	-12.810	379.2	80.0
Load5 Bus	11	96.798	-3.9	0	0	6.746	3.092	Bus19	-6.746	-3.092	402.4	90.9

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		% V_d,
ID	MW	MVAR	MW	MVAR	kW	kVAR	From	To	Drop in V_{mag}
Branch losses before compensation									
T1	11.772	8.256	-11.739	-7.636	33.3	619.3	100.0	97.4	2.60
T2	23.135	17.080	-23.098	-15.841	36.4	1239.9	100.0	97.4	2.60
T3	11.676	8.391	-11.650	-7.771	26.1	619.7	100.0	97.4	2.60
T1A	7.167	5.775	-7.145	-5.359	22.4	416.2	97.4	94.5	2.89
T2A	8.737	2.211	-8.587	-1.840	**150.0**	370.4	97.4	94.9	2.49
T3A	6.488	5.191	-6.470	-4.852	**18.2**	339.2	97.4	94.8	2.60
					286.4	**3,604.6**			
Branch losses after compensation									
T1	12.092	4.531	-12.065	-4.031	26.9	499.5	100.0	98.5	1.49
T2	23.955	9.649	-23.926	-8.649	29.3	1000.0	100.0	98.5	1.49
T3	12.039	4.670	-12.018	-4.170	21.1	499.8	100.0	98.5	1.49
T1A	7.509	3.417	-7.491	-3.090	17.6	326.8	98.5	96.8	1.75
T2A	9.089	0.315	-8.940	0.053	149.3	368.7	98.5	96.8	1.67
T3A	6.761	3.366	-6.746	-3.092	**14.7**	273.9	98.5	96.8	1.71
					258.8	**2,968.7**			

Table 4. Percentage improvement of the bus voltages of the Maryland network

Bus ID	Voltage Magnitude (%)		Voltage Improvement (%)
	Before Compensation	After Compensation	
Load1 Bus	94.506	96.767	2.261
Load2 Bus	97.396	98.512	1.116
Load3 Bus	94.908	96.838	1.930
Load4 Bus	97.396	98.512	1.116
Load5 Bus	94.792	96.798	2.006

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 150.0kW 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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