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Power Flow Study for Improvement of Port Harcourt Town 132/33kV Substation in Nigeria

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Abstract- In Port Harcourt, Nigeria, there is an ever growing load demand on the electrical power distribution systems. As a result, there is a need to regularly improve the existing system or introduce new systems for an optimal performance. The determination of best operating conditions for existing systems and the planning of new systems to be introduced require power flow analysis to find out the various levels of deficiency in the network. This study examines the power flow status of the Port Harcourt Town 132/33kV substation network under maximum loading conditions to improve its performance. The network has 165MVA 132/33kV and 45 MVA 33/11kV installed capacity transformers feeding 12 injection substations. Newton-Raphson power flow solution technique was used to analyze the network in Electrical Transient Analyzer Program (ETAP 16.0.0) software. The base-case and post-upgrade state simulation results were presented in the analysis. The results obtained for the base-case simulation revealed the areas in the network that need urgent attention. With the improvement techniques employed in this study, all the substation components operated within the acceptable performance limits and a high power loss reduction was achieved. The study proffered solutions for operating the substation during peak demands for electrical power.

Keywords- *Distribution System, Maximum Loading Condition, Newton-Raphson Power Flow Method, ETAP Software, Power Loss Reduction*

I. INTRODUCTION

In a power network, active and reactive power move from the generating stations to the load past various network buses and branches. The flow of active and reactive power is named the power flow or load flow. Power flow or load flow study is the term assigned to a network solution that gives the steady-state currents, voltages and real and reactive power flows past every branch and bus in the network. The electrical feedback of the power system is given by this power flow computation for a specific set of loading and supply power output (IEEE, 2018).

Operating scenarios that cannot be practically encountered on the actual system are simulated via power flow studies because the system is yet to be built, because of the possible limitations of time, or because it would be ill-advised to bare the actual system to situations that would likely be harmful. The end target of the power flow study is not always to end up at hard, numerical performance parameters. Usually the target is to gain insight into how the network behaves over a range of operating scenarios (IEEE, 2018). Information acquired from power flow studies are key for the continuous observation of the present state of the system and for analysis of how effective substitute plans are for future extensions to meet the growing load demand (Gupta, 2012). Thus a power flow study is an essential tool utilized by power system engineers for planning and determining the steady-state performance of a power system.

Short-circuit, motor starting, stability and harmonic studies are some other types of power system studies that utilize the power flow model as the basis for analysis. The system data and an initial steady-state condition are provided by the power flow model for these studies.

For a long time, power flow studies were done with special purpose analog computers known as the alternating current (ac) network analyzer, but the invention of high speed digital computers has replaced their use for larger network studies. This switch from the ac network analyzer to the digital computer has led to better flexibility, economy, accuracy and quicker operation (Gupta, 2012).

For three decades, many numerical analysis techniques have been utilized in solving power flow analysis problems. The frequently used iterative techniques are the Gauss-siedel, the Newton – Raphson and Fast Decoupled methods. Nowadays, many improvements have been introduced to those techniques involving assumptions and approximations of system data, based on real system scenarios (Idoniboyeobu & Ibeni, 2017). The evolution of these techniques is, for the most part, led by the basic necessities of power flow computation such as computing efficiency, memory required, convenience, convergence properties, and flexibility of the implementation.

Newton-Raphson power flow iterative technique was used for the analysis in this study because of its speedy convergence rate and high accuracy when set side by side with other solution algorithms (Afolabi et al., 2015). Using relevant data obtained from the Port Harcourt Electricity Distribution Company (PHED) and Transmission Company of Nigeria (TCN), the Port Harcourt Town 132/33kV substation is modeled and simulated with Electrical Transient Analyzer Program (ETAP). ETAP is a powerful graphical user interface (GUI) power system with the ability to model and simulate power system networks.

II. MATERIALS AND METHODS

A. *Materials*

The materials used for the analysis include:

1. Network Layout from power supply to the base-case substation
2. Electrical Transient Analyzer Program (ETAP 16.0.0) software
3. Substation feeders data
4. Substation components ratings

1) Description of the Substation

The Port Harcourt Town 132/33kV substation gets power from Afam transmission station via a 132kV double circuit transmission line connected to the national grid at Alaoji-Afam transmission station. The substation consists of 165 MVA 132/33kV and 45 MVA 33/11kV installed capacity transformers. The substation has twelve (12) feeders: six 33kV feeders and six 11kV feeders feeding injection substations in the zone. Figure 1 shows the base-case network of the Port Harcourt Town 132/33kV substation modeled with ETAP software.

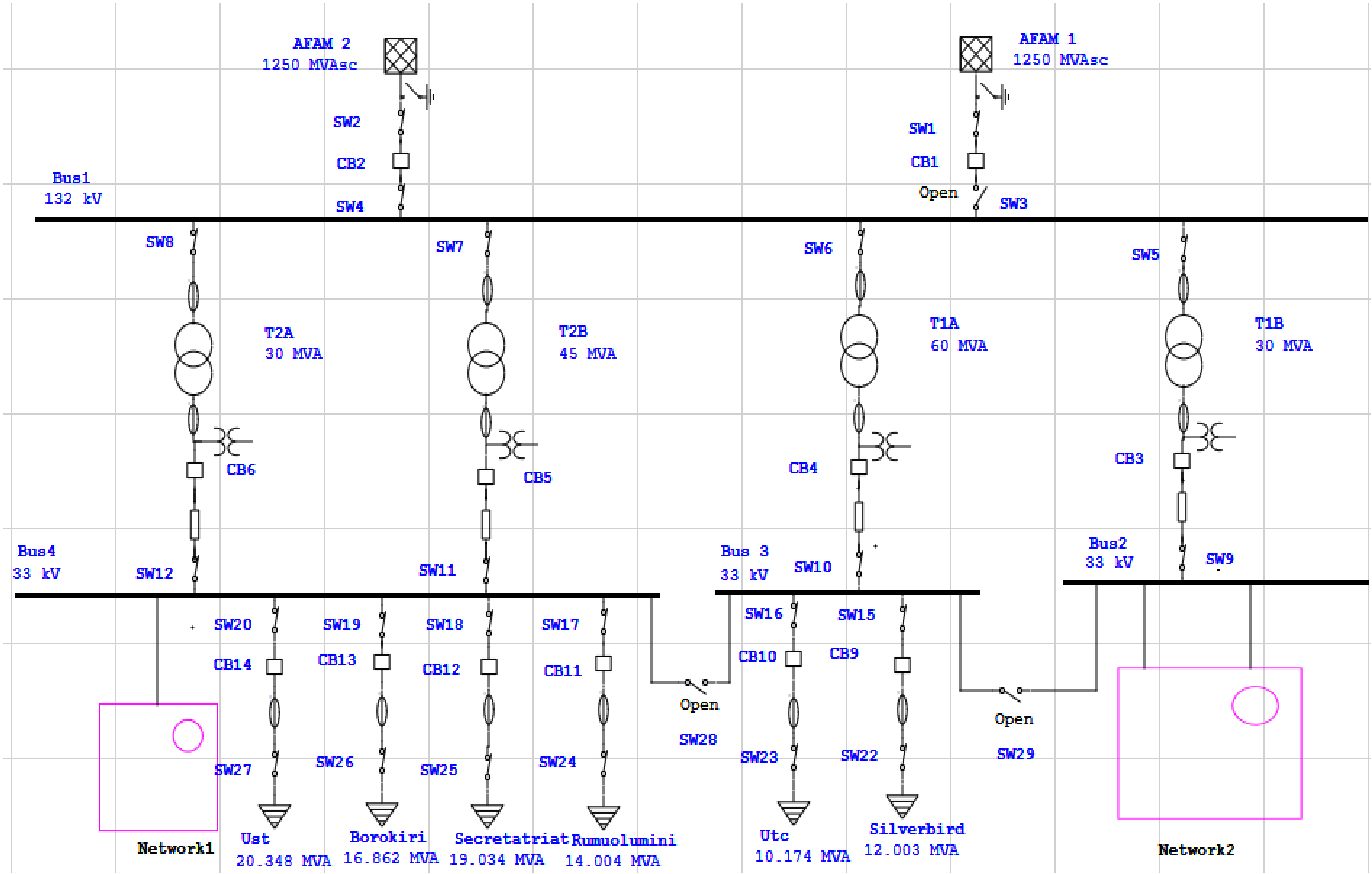

Figure 1. The Base-Case Network of the Port Harcourt Town 132/33kV Substation

Table 1 shows the substation data used for this analysis that were obtained from the public energy service provider, PHED.

TABLE I. PORT HARCOURT TOWN 132/33KV SUBSTATION DATA

Component	Type	Rating	
Power Transformer	T1A T1B T2A T2B T1BA T1BB T3	60 MVA (132/33kV) 30 MVA (132/33kV) 30 MVA (132/33kV) 45 MVA (132/33kV) 15 MVA (33/11kV) 15 MVA (33/11kV) 15 MVA (33/11kV)	
Circuit Breaker	CB 1, 2 CB 3 – 6 CB 7 – 15 CB 16 – 18 CB 19 - 25	145 kV/1600A 34 kV/1250A 34 kV/1250A 12 kV/1250A 12 kV/1600A	
Cable	1 – 4 Aluminium conductor steel reinforced with galvanized	185mm^2 ACSR/GZ	
Current Transformer		Primary	Secondary
	CT 1 – 4 CT 5 – 8 CT 9 – 17	200 A 1200 A 1200 A	1A 5A 5A
Potential Transformer	PT 1 - 4	33/0.415 kV	
Isolating Switches	SW 1 – 8 SW 9 - 29	132kV/1600A 33kV/1250A	
Feeders	Amadi South	260A	
	Owerri Road	221A	
	UST	356A	
	Borokiri	295A	
	Secretariat	333A	
	Rumuolumini	245A	
	UTC	178A	
	Silverbird	210A	
	Mile One	285A	
	Spare	220A	
	Old diobu	254A	
	Trans Amadi Residential	247A	

Source: PHED, (2020).

B. *Methods*

The network base-case data acquired were used to model the system using ETAP 16.0.0 software. The simulation was carried out with Newton-Raphson power flow solution method embedded in the software to compute the unknown parameters of the network under maximum loading condition. Thereafter, the evaluation of component or circuit loadings, operating voltages, real and reactive power flows past every branch and bus in the system were carried out; which revealed the parts of the substation network that need urgent attention.

Improvement techniques such as upgrading of power system facilities (i.e. transformer rated capacity and tap changer setting) and adding Flexible Alternating Current Transmission Systems (FACTS) devices (i.e. using sizeable switched capacitor banks) were then applied to optimize the performance of the existing base-case substation. Finally, a comparative analysis was performed between the base-case and the improved state for a validation of the improved performance of the substation.

1) Formulation of Bus Admittance Matrix

The formulation of the bus admittance matrix is programmed in the power flow software. Nevertheless, it is still beneficial to understand the general principles used in the process of creating the matrix.

The basic rules used for formulating the Y matrix are:

i. The diagonal terms Y_{ii} are the sum of admittances of the lines leaving a bus, plus the admittance of any shunt elements connected to the bus, plus one-half of the charging admittance defined for each connected line. This means that the admittance matrix will always be a square matrix in which the number of diagonal elements equals the number of buses in the system model.

ii. The off-diagonal terms Yik are the negative of the line admittances between buses i and buses k, where a link between bus i and bus k exists. If there is no link between bus i and bus k the ik term is zero.

$$Y_{ik} = -1/Z_{ik} \tag{1}$$

The Y matrix is usually very sparse (i.e. most of the off-diagonal terms are zero) because not every possible pair of nodes in the system would be connected (IEEE, 2018).

2) Newton-Raphson Iterative Technique

The Newton-Raphson method for solving power flow problems is based on the Taylor’s series expansion for a function of two or more variables (Ibe, 2002). The approach utilizes the partial derivatives of the power flow relationships to estimate the changes in the independent variables required to find the solution (IEEE, 2018).

From Kirchhoff’s current law, the current injected into the ith bus of an n bus system is given as

$$\begin{aligned} I_i &= \mathrm{Y}_{i1}\mathrm{V}_1 + \mathrm{Y}_{i2}\mathrm{V}_2 + \mathrm{Y}_{i3}\mathrm{V}_3 + \ \ldots \\ &\quad + \mathrm{Y}_{in}\mathrm{V}_n;\ \mathrm{i} = 1,\ 2,\ 3,\ \ldots,\ \mathrm{n} \\ &= \sum_{k=1}^{n} \mathrm{Y}_{ik}\ V_k;\ \ i = 1,\ 2,\ 3, \ldots, n \end{aligned} \tag{2}$$

where

V_k = bus voltage at bus k given as $|V_k|\angle\delta_k$; δ_k is the phase angle at node k

Y_{ik} = admittance between bus i and bus k given as $\mathrm{Y}_{ik}\angle\theta_{ik};\theta_{ik}$ is the admittance angle between nodes i and k

The complex power injected by the generating source into an ith bus of a power system is given as

$$S_i = P_i + j\,\mathrm{Q_i} = I_i^* \, V_i \;;\; i = 1, 2,3, \dots , \mathrm{n} \qquad (3)$$

where

P_i = Real power injected into the ith bus

Q_i = Reactive power injected into the ith bus

I_i^* = Complex conjugate of source current I_i injected into the ith bus

V_i = Voltage at bus i with respect to ground given as $|V_i|\angle\delta_i$; δ_i is the phase angle at node i

It is convenient to handle power flow problems using I_i rather than I^*. So taking the complex conjugate of (3), we have

$$S_i{*} = P_i \text{ -} j\,\mathrm{Q_i} = I_i \;\; V_i{*};\;\; i = 1, 2, 3, \dots, \mathrm{n} \qquad (4)$$

where V_i^* is the complex conjugate voltage of the ith bus respect to ground given as $|V_i|\angle-\delta_i$

Substituting (2) into (4) we have

$$S_i{*} = P_i - j\,\mathrm{Q_i} = \sum_{k=1}^{n} Y_{ik} V_k \;\mathrm{V_i}{*};\; i = 1, 2, ---, \mathrm{n} \qquad (5)$$

substituting the values of $V_i{*}, V_k$ and Y_{ik} into (5) we have

$$P_i \text{ -}j\;\mathrm{Q_i} = \sum_{k=1}^{n} \left| Y_{ik} V_k \;\; V_i \right| \;\angle\theta_{ik} + \delta_k - \delta_i \qquad (6)$$

separating the real and imaginary parts, we get

$$P_i = Real = \sum_{k=1}^{n} \left| Y_{ik} V_k \;\; V_i \right| \cos\left(\theta_{ik} + \delta_k - \delta_i\right) \qquad (7)$$

and

$$Q_i = \text{Imaginary} = -\sum_{k=1}^{n} \left| Y_{ik} V_k \;\; V_i \right| \sin\left(\theta_{ik} + \delta_k - \delta_i\right) \qquad (8)$$

for i = 2, 3, 4 - - - - -, n as bus 1 is slack bus

Equations (7) and (8) constitute the polar form of the power flow equation that provide the calculated values for the net real power P_i and reactive power Q_i entering the network at bus i.

Denoting the calculated values of P_i by $P_{i,calc}$ and of Q_i by $Q_{i,calc}$ leads to the definition of mismatches ΔP_i and ΔQ_i.

$$\left.\begin{aligned} \Delta P_i &= P_{i,sch} - P_{i,calc} \\ \Delta Q_i &= Q_{i,sch} - Q_{i,calc} \end{aligned}\right\} \qquad (9)$$

where $P_{i,sch}$ and $Q_{i,sch}$ are the net real and reactive scheduled power injected into bus i. Mismatches occur when $P_{i,calc}$ and $Q_{i,calc}$ do not coincide with the scheduled values.

The linear equations inter-relating the changes in power with change in real and reactive components of the bus voltages can be written in polar form as:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta_i \\ \Delta|V_i| \end{bmatrix} \qquad (10)$$

where J is a matrix of partial derivatives known as a Jacobian

$$\mathrm{J} = \begin{bmatrix} \dfrac{\partial P}{\partial\delta} & \dfrac{\partial P}{\partial|V|} \\ \dfrac{\partial Q}{\partial\delta} & \dfrac{\partial Q}{\partial|V|} \end{bmatrix} \qquad (11)$$

The unknown quantities $\Delta\delta, \Delta|V_i|$ can be obtained by expressing the linear (10) as

$$\begin{bmatrix} \Delta\delta_i \\ \Delta|V_i| \end{bmatrix} = \mathrm{J}^{-1} \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} \qquad (12)$$

The linearized system of equations is solved to determine the next guess ($r + 1$) of voltage magnitude and angle based on

$$\left.\begin{aligned} \delta_i^{\,r+1} &= \delta_i^{\,r} + \Delta\delta_i \\ |V_i|^{r+1} &= |V_i|^{r} + \Delta|V_i| \end{aligned}\right\} \qquad (13)$$

The process continues until a stopping condition is met.

The chosen method for power flow analysis (The Newton-Raphson method) is embedded in the ETAP 16.0.0 software used for the simulation. Figure 2 shows the flowchart for power flow solution using the Newton-Raphson method.

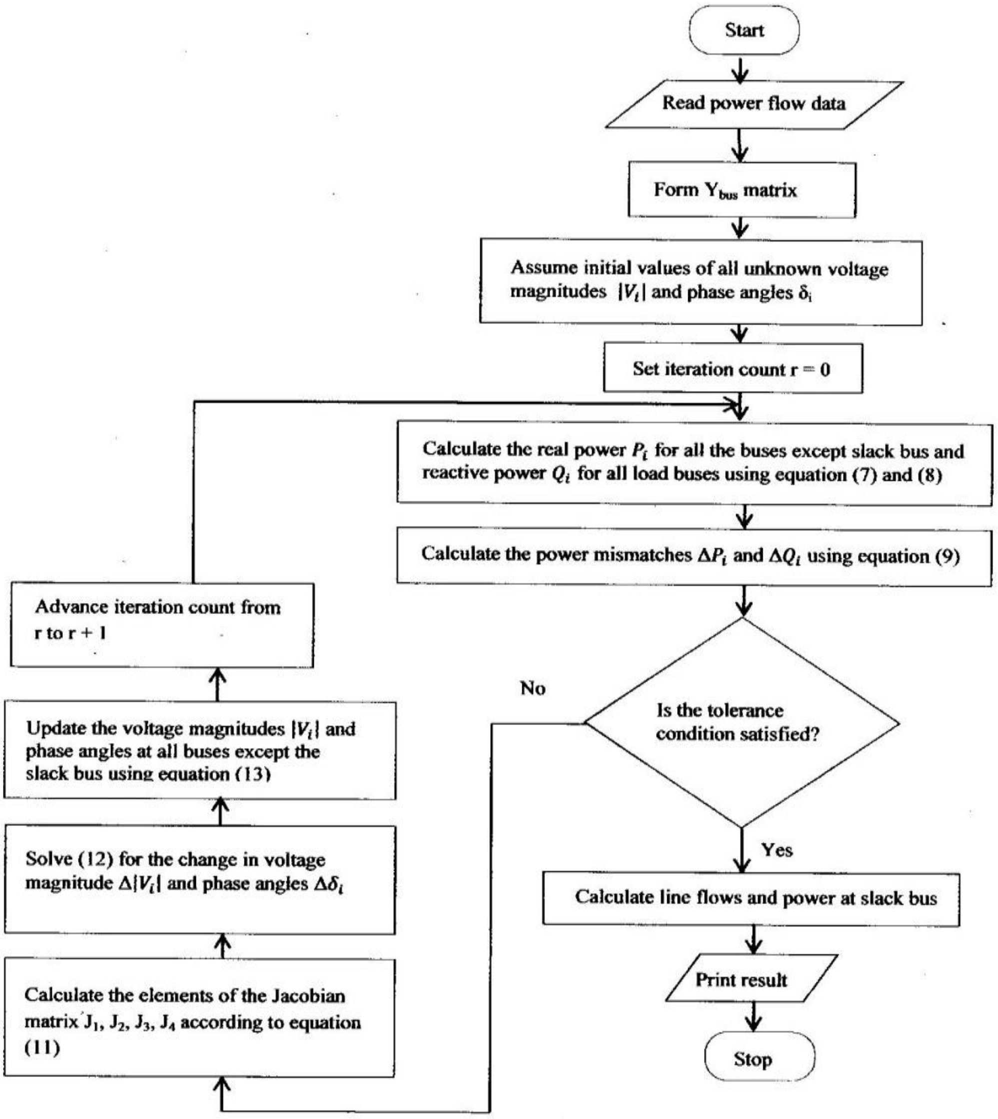

Figure 2. Flowchart for the Power Flow Solution Using Newton-Raphson Method

3) *Transmission Line Parameters*

The conductor used was Aluminium Conductor Steel Reinforced (ACSR) of 185mm^2 cross sectional area with total line length within the area estimated to be 0.25km. The conductors are horizontally arranged and were estimated to be spaced 4.8 metres apart.

a) Per kilometre resistance of the line (Idoniboyeobu & Ibeni, 2017)

$$R_o = \frac{\rho 1000}{A} \ \Omega/\text{km} \tag{14}$$

where

ρ is the resistivity of aluminum at 22^{o}C –30^{o}C=2.82×10^{-8} Ωm

A is the area of the conductor

$$R_o = \frac{2.82\times10^{-8}\,\Omega/1000m}{1.85\times10^{-4}\,m^2} = 0.1524\Omega/km$$

b) Per kilometre reactance of the line (Idoniboyeobu & Ibeni, 2017)

$$X_o = 0.1445\ Log_{10}\left[\frac{D_{GMD}}{r}\right] + 0.0157\ \Omega/\text{km} \tag{15}$$

D_{GMD} is the geometric mean distance of the conductor

$$= \sqrt[3]{D_{RY}\cdot D_{YB}\cdot D_{RB}} = 1.26\text{ D} \tag{16}$$

where D is the distance between adjacent conductors

= 1.26 × 4.8 = 6.048m

The radius of the conductor is

$$r = \sqrt{\frac{A}{\pi}}\ \text{m} = \sqrt{\frac{1.85\times10^{-4}}{3.142}} = 7.6733\times10^{-3}\,m \qquad (17)$$

Therefore, from (15)

$$X_o = 0.1445\ Log_{10}\left[\frac{6.048}{7.6733\times10^{-3}}\right] + 0.0157 = 0.4343\ \Omega/\text{km}$$

c) Per kilometre capacitive susceptance of the line (Idoniboyeobu & Ibeni, 2017)

$$B_o = \frac{7.58}{Log_{10}\left[\frac{D_{GMD}}{r}\right]} \times 10^{-6}\ \text{S/km} \qquad (18)$$

$$B_o = \frac{7.58}{Log_{10}\left[\frac{6.048}{7.6733\times10^{-3}}\right]} \times 10^{-6}$$

$$B_o = 2.6168 \times 10^{-6}\ \text{S/km}$$

d) Per kilometre impedance of the line (Idoniboyeobu & Ibeni, 2017)

$$Z = R_o + j\ X_o\ \ \Omega/\text{km} \qquad (19)$$

$$Z = \sqrt{{R_o}^2 + {X_o}^2} = \sqrt{0.1524^2 + 0.4343^2} = 0.4603\ \ \Omega/km$$

4) *Peak Load for the Substation*

The peak load is the maximum load on an electrical power supply system. Taking the Amadi South feeder as an example, we have

Peak load (I_L) = $I_1 + I_2 + I_3 + - - - + I_n$ (20)

=260 A (Direct reading from substation Logbook)

Peak Load (MVA) = $\sqrt{3}\times I_L \times V_L \times 10^{-6}$ (21)

where

I_L = total peak loads of respective feeders at the substation in Amperes

V_L = line voltage of the feeder in kilovolts

Peak load (MVA) = $\sqrt{3}\times260\times11000\times10^{-6}$ = 4.954 MVA

Peak load (MW) = MVA × power factor (cos θ) (22)

= 4.954 x 0.85 = 4.211 MW

Peak load (MVAR) = $\sqrt{MVA^2 - MW^2}$ (23)

= $\sqrt{4.954^2 - 4.211^2}$ = 2.610 MVAR

Using (20), (21), (22), (23) the various peak loads for all the feeders in the substation are evaluated and shown in Table II:

TABLE II. PEAK LOADS FOR THE SUBSTATION

S/N	Feeder	kV	MVA	MW	MVAR	% PF	Amps
1.	Amadi South	11	4.954	4.211	2.610	85	260
2.	Owerri road	11	4.211	3.579	2.218	85	221
3.	UST	33	20.348	17.296	10.719	85	356
4.	Borokiri	33	16.862	14.332	8.882	85	295
5.	Secretariat	33	19.034	16.178	10.027	85	333
6.	Rumuolumini	33	14.004	11.903	7.377	85	245
7.	UTC	33	10.174	8.648	5.360	85	178
8.	Silverbird	33	12.003	10.203	6.323	85	210
9.	Mile One	11	5.430	4.615	2.860	85	285
10.	Spare	11	4.192	3.563	2.208	85	220
11.	Old diobu	11	4.839	4.113	2.549	85	254
12.	Trans Amadi Residential	11	4.706	4.000	2.479	85	247

5) *Transformer Loading Condition*

To determine the percentage loading of transformers in the network the apparent power performance index is utilized. A transformer with loadings over 70% is overloaded based on the principle of loading distribution transformers (Amesi et al, 2017).

$$\%\ \text{Loading} = \sum_{i=1}^{N_T}\left(\frac{S_{MVA}}{S_{MAx}}\right)\times\frac{100\%}{1} \qquad (26)$$

where

S_{MVA} = The operating MVA from power flow computation

S_{MAX} = The MVA rating of the transformer

N_T = The number of transformers

6) *Bus Operating Voltage Percent*

To be within limit for critical level, bus voltages less than 95% are treated as undervoltage with those above 105% as overvoltage. Also, for marginal level, bus voltages less than 98% are treated as undervoltage and those above 102% as overvoltage.

$$\%\ \text{Bus operating voltage level} = \frac{V_R}{V_S}\times\frac{100\%}{1} \qquad (27)$$

where

V_R = Receiving end voltage in Kilovolts

V_S = Sending end voltage in kilovolts

7) *Voltage Drop*

Voltage drop is the decease of electrical potential along the path of a current flowing in an electrical circuit.

$$Voltage\ \ Drop\left(V_d\right) = Sending\ \ End\left(V_s\right) - \text{Re}ceiving\ End\left(V_R\right) \qquad (28)$$

8) *Percentage Voltage Regulation*

Voltage regulation is the change in voltage at the receiving end (or load) when the full load is thrown off, the sending end (or supply) voltage and supply frequency remaining unchanged.

$$\% \text{ Voltage Regulation} = \frac{V_S - V_R}{V_R} \times \frac{100\%}{1} \quad (29)$$

At a receiving end the maximum acceptable voltage drop percent must not be larger than ±5% of the nominal terminal voltage (IEEE, 2018).

9) Transformer Load Tap Changer

A tap changer is a mechanism in transformers which allows for variable turn ratios to be selected in distinct steps.

$$\frac{N_2}{N_1} = \frac{V_2}{V_1} = k \text{ (Turn ratio)} \quad (30)$$

$$\% \text{ Tap setting} = (k-1) \times 100\% \quad (31)$$

where

k = Turn ratio
V_2 = Receiving end voltage
V_1 = Sending end voltage

For each transformer,

Number of taps = 33 (16 to each side of the rated tap)

Maximum allowable variation = ± 10%

A single step = ± 0.625% of the nominal rating

The sending end and receiving end operating voltages for transformer TIBA are 10.806 kV and 10.416 kV, respectively. The % tap setting for improvement is calculated using (30) and (31), thus:

$$k = \frac{10.416}{10.806} = 0.9636$$

% Tap setting = (0.9636 – 1) × 100% = -3.61%

The tap position based on the operating conditions = - 3.75%

Selecting – 3.75% tap setting on the primary winding will reduce the primary turn N_I by 3.75%, thereby increasing the secondary voltage output.

10) Capacitor Bank

Most loads in modern electrical power systems are inductive (Eaton, 2014). In distribution substations, switched shunt capacitor banks (as the load power factor changes overtime) that supply reactive power (MVAR) are used to correct poor power factor caused by inductive loads, in order to reduce the line current and the power losses associated with the feeder.

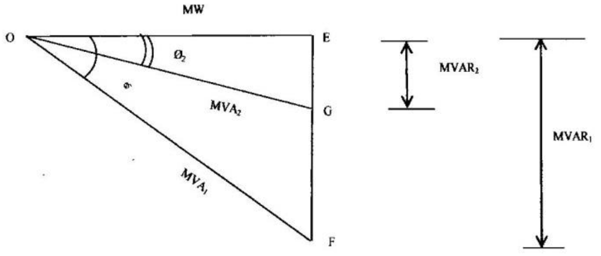

Figure 3. Power Triangle Illustrating Power Factor Correction

From Figure 3, the lagging MVAR at the load bus is reduced by the power factor (p.f.) correction device, thus improving the p.f to cos $\varnothing_2$

The leading MVAR supplied by the p.f correction device (capacitor bank)

$$\begin{aligned} GF &= EF - EG \\ &= MVAR_1 - MVAR_2 \\ &= OE\,(\tan\varnothing_1 - \tan\varnothing_2) \\ &= MW\,(\tan\varnothing_1 - \tan\varnothing_2) \quad (32) \end{aligned}$$

where

$\varnothing_1$ = Cos^{-1} initial power factor
$\varnothing_2$ = Cos^{-1} required power factor
MW = Real power/Actual load power in megawatts

Taking bus 3 as an example, the required capacitor bank size for improvement can be calculated from (32):

$\varnothing_1$ = 0.85
$\varnothing_2$ = 0.95
MW = 17.881 MW

Required capacitor size=17.881(tan($\cos^{-1}$ 0.85) – tan($\cos^{-1}$ 0.95))

= 5.21 MVAR

11) Power Loss Reduction

Losses as a result of poor power factor are caused by reactive current flowing in the system. These losses can be reduced through power factor correction (Eaton, 2014). To calculate loss reduction:

$$\% \text{ reduction losses} = \frac{P_B - P_A}{P_B} \times \frac{100\%}{1} \quad (33)$$

where

P_B = Apparent losses of the system before improvement
P_A = Apparent losses of the system after improvement

III. RESULTS AND DISCUSSION

A. *Results*

The results obtained for the Port Harcourt Town 132/33kV substation analysed with Newton-Raphson power flow solution method under maximum loading condition, before and after improvements are presented.

Table III is the pre-and post-upgrade transformer loading simulation results for the substation, Table IV shows the bus voltage profile before and after improvement and Table V is the summary of the total demand and losses for the substation before and after improvement.

TABLE III. PRE- AND POST-UPGRADE TRANSFORMER LOADING SIMULATION RESULTS FOR THE SUBSTATION

S/N	Device Id	Device Capacity (MVA)		Operating Capacity (MVA)		% Substation Loading	
		Before Upgrade	After Upgrade	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade
1.	T1A	60	60	21.59	19.617	35.98	32.7
2.	T1B	30	80	17.621	19.55	58.73	24.4
3.	T1BA	15	15	8.382	9.558	55.88	63.7
4.	T1BB	15	15	8.447	9.632	56.31	64.2
5.	T2A	30	80	29.350	33.643	97.83	42.1
6.	T2B	45	80	43.883	33.643	97.52	42.1
7.	T3	15	15	7.590	9.392	50.60	62.6

TABLE IV. BUS VOLTAGE PROFILE OF THE SUBSTATION BEFORE AND AFTER IMPROVEMENT

S/N	Device Id	Rating (kV)	Operating voltage in magnitude (kV)		Voltage Drop (kV)		% Operating Voltage Level		Percentage Voltage Regulation	
			Before Upgrade	After Upgrade	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade
1.	Bus 1 (Swing)	132	132	132	0	0	100	100	0	0
2.	Bus 2	33	31.498	32.374	1.502	0.626	95.45	98.103	4.77	1.93
3.	Bus 3	33	32.141	32.487	0.859	0.513	97.40	98.445	2.67	1.58
4.	Bus 4	33	30.566	32.726	2.434	0.274	92.62	99.170	7.96	0.84
5.	Bus 5	11	10.120	10.806	0.88	0.194	92.00	98.236	8.70	1.80
6.	Bus 6	11	10.117	10.803	0.883	0.197	91.97	98.209	8.73	1.82
7.	Bus 7	11	9.835	10.940	1.165	0.06	89.41	99.455	11.85	0.55

TABLE V. SUMMARY OF TOTAL DEMAND AND LOSSES FOR THE SUBSTATION BEFORE AND AFTER IMPROVEMENT

type	MW		MVAR		MVA		% Power Factor	
	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade	Before Upgrade	After Upgrade
Source (Swing Bus)	89.542	100.697	67.941	28.179	112.400	104.566	79.66 Lagging	96.30 Lagging
Total Demand	89.542	100.697	67.941	28.179	112.400	104.566	79.66 Lagging	96.30 Lagging
Total Static Load	89.120	100.416	55.231	21.505	104.847	102.693	85.00 Lagging	97.78 Lagging
Apparent Losses	0.423	0.281	12.709	6.675				

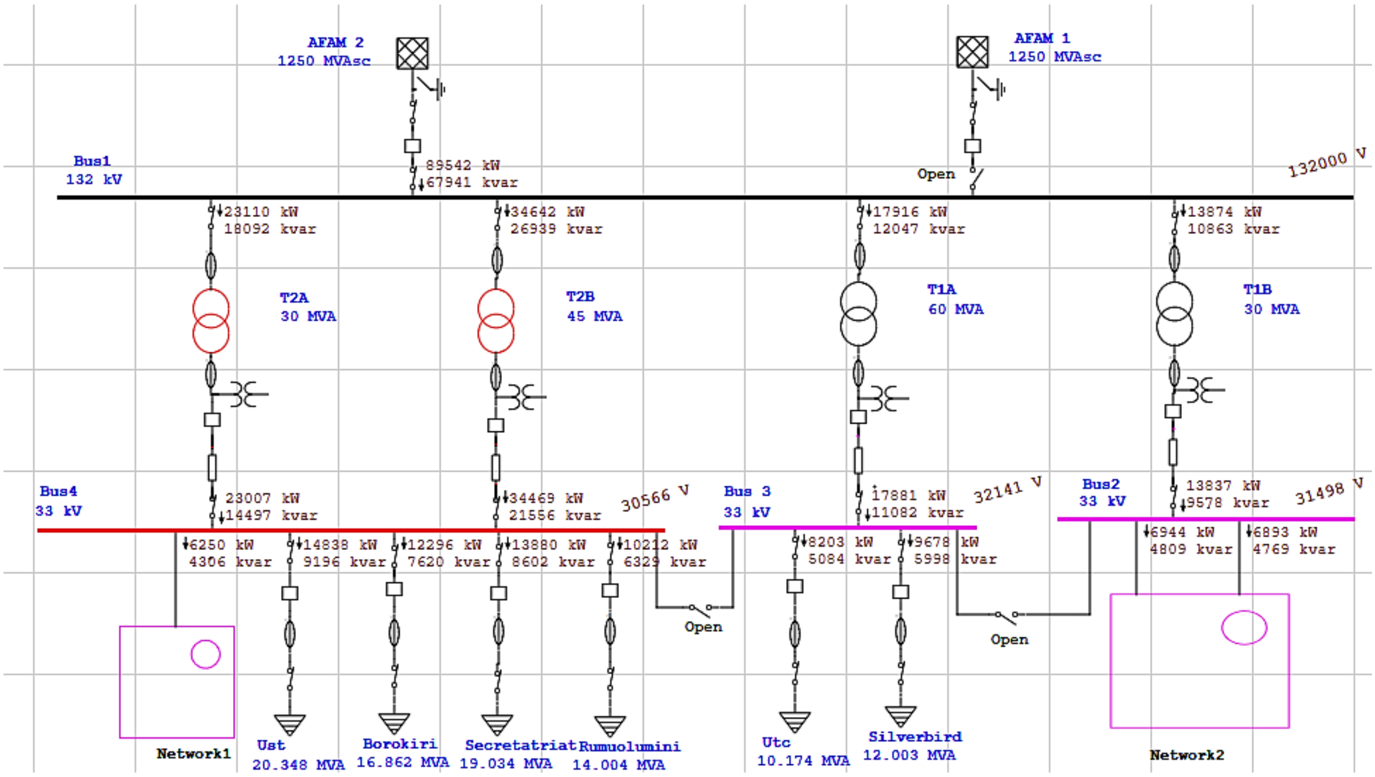

Figure 4. Pre-Upgrade Simulation of the Base-Case Substation

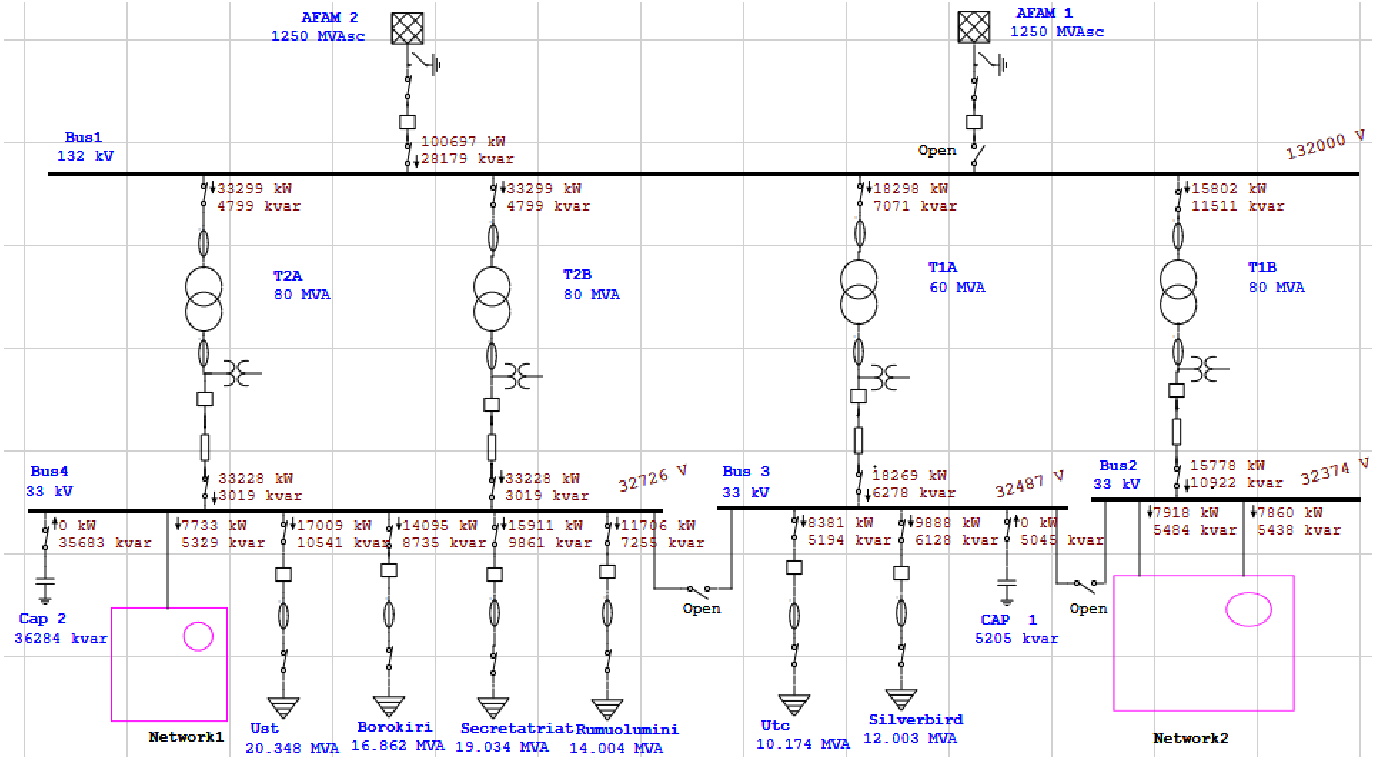

Figure 5. Post-Upgrade Simulation of the Base-Case Substation

Figure 4 shows the pre-upgrade simulation of the base-case substation while Figure 5 shows the post-upgrade simulation of the substation. Figure 6 shows the substation transformer loadings for both pre-and post-upgrade while Figure 7 shows the percentage voltage profile of the buses for both the pre- and post-upgrade states.

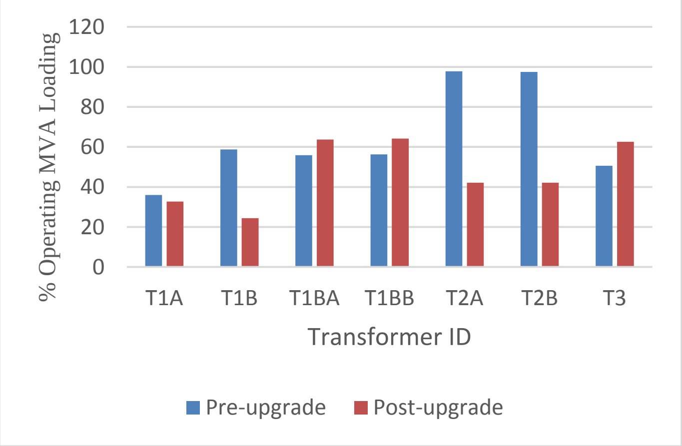

Figure 6. Transformers Operating MVA for both Pre and Pre-Upgrade

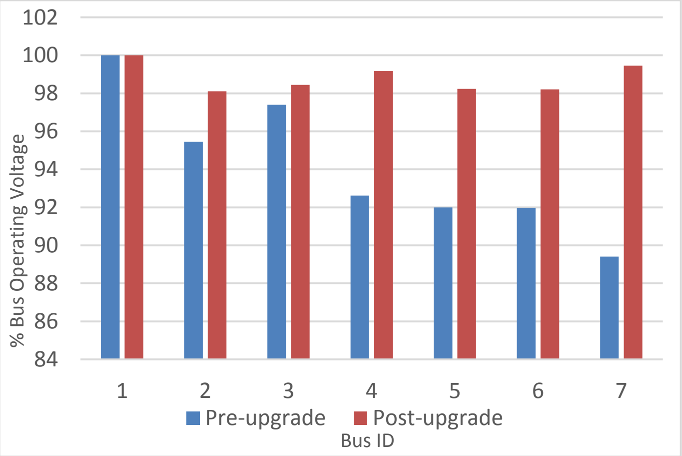

Figure 7: Voltage Profile for both Pre and Post-Upgrade State

B. *Discussion*

Figure 4 shows the Port Harcourt Town base-case power system simulated using ETAP 16.0.0 before applying techniques to improve the operating state. Virtually all the buses are signaling an undervoltage state apart from the reference 132kV bus 1 which is operating at a normal state. Buses 2 and 3 are operating at marginal undervoltage level (purple color) while buses 4, 5, 6 and 7 are operating at critical undervoltage level (red color). A critical alert (red color), signaling an overload state, was also indicated for transformers T2A and T2B.

Figure 5 shows the simulation of the base-case substation after improvements without any critical or marginal alert on the loading condition. Transformers T1B, T2A and T2B were upgraded to 80MVAs, load tap changer action was performed on transformers T1BA, T1BB and T3, while capacitor banks were added to buses 3 and 4 for improvement.

Figure 6 shows that transformers T2A and T2B were operating at 97.83% and 97.52% respectively, which is above 70% of its design rated capacity, therefore are overloaded. After upgrade, the overloaded transformers T2A and T2B were both operating at 42.1% of their design rated capacity and were no longer overloaded.

Figure 7 shows that the bus voltages are operating within limit with a minimum and maximum value of 98.103% and 99.455%, respectively. At a receiving end the maximum acceptable voltage drop percent must not be larger than ±5% of the nominal terminal voltage (IEEE, 2018). Thus, the lowest value recorded is 0.55% drop while the highest is 1.93% drop.

Finally, comparing the values of Table V, it can be seen that the substation power factor was improved from 79.66% lagging to 96.30% lagging thereby reducing the system apparent losses. A 47.461% reduction in power loss of the base-case results was achieved.

IV. CONCLUSION AND RECOMMENDATION

A. *Conclusion*

Power flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. In this study, the Port Harcourt Town 132/33kV substation network was modeled with ETAP to perform power flow analysis.

The analysis was done using Newton-Raphson power flow solution technique under maximum loading condition. The Newton-Raphson algorithm is embedded in the ETAP software used to perform the simulation.

From the simulation results, the parts of the substation network that need urgent attention when operating under maximum loading condition were clearly revealed. A low power factor was recorded, as a result of transformer overload, poor voltage profile at the buses and high apparent power losses.

Due to the results of the analysis, improvement techniques, such as the upgrade of transformer rated capacity, proper transformer load tap changer settings, and placement of switched capacitor banks in shunt with the feeders, were introduced to optimize the performance of the system.

The results of the power flow analysis of the substation after the introduction of optimization techniques compared with the existing state show that the system power factor improved and, correspondingly, there was an improvement in the voltage profile of the network, transformer loading condition and the reduction of apparent losses.

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