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Comparative Application of Load Tap-Changing Transformer (LTCT) and Shunt Capacitor for Voltage Profile Enhancement on Nigerian 330kV, 24-Bus Transmission System

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ABSTRACT: ***The use of conventional devices as control mechanism for system voltage profile enhancement and loss reduction is still predominantly prevalent in most third world nations and Nigeria is never an exemption. This study seeks to compare efficiency of Load Tap-Changing Transformer and Shunt Capacitors using system voltage profile enhancement and real power loss minimization as performance matrix on Nigerian 330kV, 24-Bus grid system as a test case. In this work, the Newton Raphson iterative algorithm was adopted due to its superior features over other iterative techniques. Load flow analysis was performed on the test case with and without incorporation of LTCT and Shunt Capacitors, the result of the analysis shows that with shunt capacitors injection at the weak buses identified, the algorithm converged in 5 iterations but with LTC transformer convergence was achieved in 4 iterations. Also, the total system losses with shunt capacitor injection was found to be 82.2826MW which is about 4.1% reduction while with LTC transformer, the total system losses reduced appreciably to 81.9865MW which is about 4.8% reduction. Incorporation of LTCT gives a better improvement on system voltage profile compared with the improvement observed with shunt capacitor injection at the defective buses identified.***

Keywords: *Load Flow Analysis, Load Tap-Changing Transformer (LTCT), Newton-Raphson Iterative Method, Shunt Capacitors Injection, Voltage Profile Enhancement*

I. INTRODUCTION

The Nigerian power grid system, like other power grids elsewhere is constantly being faced with problem of voltage profile fluctuation throughout the entire grid due to topological differences between transmission and distribution systems, hence voltage control in an electrical power system is indeed imperative for efficient and adequate operation of vast number of electrical power equipment connected by different types of customers at the distribution end of the power system. Several methods and devices has been used by many researchers in the literatures, those methods were based on the concept of either injecting or absorbing reactive power using various devices ranging from discrete controllers (convectional devices) to modern power electronics devices.

At the substation stage of the grid system, load tap-changing transformer and several capacitor banks are usually employed to control the voltage magnitude [1]. In operation, the LTCT changes its tap position in an attempt to control the lower side voltage magnitude directly while on the other hand, the installed capacitor banks act on the higher side voltage magnitude indirectly by altering the amount of reactive power demanded at each bus [1, 2]. Both Load Tap- Changing Transformer and Shunt Capacitor are collectively referred to as discrete voltage controllers by virtue of their mode of operation.

In this paper, a comparative application of Load Tap-Changing Transformer (LTCT) and Shunt Capacitor for Voltage Profile Enhancement on Nigerian 330kV, 24-Bus Transmission system was carried in MATLAB environment and based on the results obtained from the simulation carried out; a comparison was made on the voltage profile enhancement ability of LTCT and Shunt Capacitor.

II. CONCEPT OF VOLTAGE STABILITY, ON LOAD TAP- CHANGING TRANSFORMER (OLTC) AND SHUNT CAPACITOR REACTIVE COMPENSATOR

Maintenance of voltage stability on transmission grid system is one of the pressing challenges in the power sector when it comes to system security particularly in developing countries of the world and Nigeria being a third world nation cannot be exempted. Voltage stability implies the ability of power system to maintain a steady acceptable voltages at all buses during normal operating conditions and also after being subjected to a disturbance [3, 4]. If the consumers' connected pieces of equipment will enjoy relatively prolong service life without malfunctioning, then effort should be made to ensure that voltages at the terminals of all equipment in the system are kept within the range of nominal values limits [3, 4]. Voltage stability deterioration is mainly due to the large amount of reactive power absorbed by consumers connected loads during continuous operation and system contingencies [5].

Several methods and devices have been used by researchers to keep voltage at each buses within the required limits, of such method includes absorption and injection of reactive power sources with the aid of these discrete devices On Load Tap Changing Transformer (OLTC) and Shunt Capacitor Injection and modern power electronics based controllers called Flexible Alternating Current Transmission System (FACTS) devices which are the emerging technologies for voltage profile enhancement on transmission grid [3, 6-10].

On Load Tap-Changing Transformers (OLTC) are discrete controllers being a special types of transformer equipped with taps on the windings for adjusting either the voltage transformation or the reactive flow through the transformer [11]. This attribute of OLTC transformers are very useful in controlling the flow of real power through a transmission system since transformers are required additionally to perform the task of regulating the active and reactive power flows. Essentially, Load tap changing transformers regulate nodal voltage magnitude by varying automatically the transformer tap ratio under load [6]. In OLTC, the off-nominal tap ratio determines the additional transformation relative to the nominal transformation and the acceptable value limits ranges from0.9 to 1.1 with 1.0 corresponding to no additional transformation and the acceptable step size variation of tap changer is 0.025 from minimum tap ratio until maximum tap ratio [7,12]. Primarily, a tap changer is governed by its step size, time constant, reference voltage and deadband [13].The essential features of OLTC transformer among others include the following;

- Switch Select: These are the physical tap positions on the transformer winding and cannot make or break the load current because of their construction style.
- Reactors (Inductors): These are used in the circuit to increase the impedance of the selector circuit and limit the amount of current circulating due to voltage difference.
- Vacuum Switch: This performs the duty of a circuit breaker that makes and breaks current during the tap changing sequence.
- Bypass Switch: This operates during the tap changing sequence and at no time does it make or break load current, even though it makes before breaking each connection.

The inherent advantages of OLTC as discrete voltage controller in power system includes ability to change voltage ratio without de-energizing the transformer, it can adjust both voltage magnitude and reactive flow and lastly, it provides finer control of voltage than would be possible with off-load taps.

Shunt capacitors are discrete simplest sources for providing the reactive power locally, they are used to deliver reactive power and increase transmission voltages during heavy load conditions [14, 15]. Shunt capacitors are usually used to inject reactive power at defective (weak) buses where voltage magnitude falls outside the acceptable voltage limit ranges of 0.95p.u to 1.05 p.u. Shunt Capacitors are simple devices with insulating dielectric placed between two parallel metal plates and when charged to certain voltage, charges are accumulated on both sides of the dielectric and in this way the charges are stored. Fundamentally in AC systems, capacitors store energy just only for one half cycles. During the first half cycle, capacitor charges up and discharges in next half cycle back to the system. This attribute explains how capacitors are used to provide the reactive power when it's needed and with this mechanism, the capacitors and reactive power loads exchange the reactive power back and forth throughout the entire system [15]. The candidate placement for shunt-type capacitor could either be installed near the load, in a distribution substation, along the distribution feeder, or in a transmission substation but at the transmission substation both inductive and capacitive reactive compensation are installed [3, 15-17]

The advantages of shunt capacitor reactive compensation on power system includes voltage regulation (control the voltage within required levels), system power losses reduction brought about by power factor improvement and lastly, it increases utilization of connected pieces of equipment at the consumer end [3].

III. PROBLEM FORMULATION

A. Newton-Raphson Based Load Flow Techniques

Solution methodologies available for solving load flow problem include Gauss-Seidel Method, Fast Decouple Newton-Raphson and Newton-Raphson method. The latter being superior to others is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion with the terms limited to the first approximation [18, 19]. It has quadratic convergence which makes it to be relatively more powerful compared with other alternative iterative processes and the reliability of Newton-Raphson approach is comparatively good, since it can solve cases that lead to divergence with other popular processes [20, 21].

With this algorithm, the voltage magnitude is held constant at 1.0 per unit and the acceptable voltage magnitude limits ranges from 0.95 p. u to 1.05 p. u, such that the candidate placements for shunt compensation are the defective buses in the system with voltage magnitude less than 0.95 per unit.

B. Power Flow Equations for Newton-Raphson Based Load Flow Technique

In a typical interconnected power system the complex power injected to a bus i is written as;

$$S_i = P_i + jQ_i = V_i {I_i}^* \tag{1}$$

$$I_i = \frac{P_i - jQ_i}{{V_i}^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad i \neq j \tag{2}$$

$$P_i - Pd_i = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad i = 1,2,3 \ldots\ldots, n \tag{3}$$

$$Q_i - Qd_i = -\sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad i = 1,2,3 \ldots\ldots, n \tag{4}$$

Where S_i = Complex power supplied to busi^{th},I_i = Current at busi^{th}, P_i= Real power generated at bus i^{th}, Q_i= Reactive power generated at bus i^{th}, Pd_i=Real power consumed at busi^{th}, Qd_i= Reactive power consumed at bus i^{th}, V is the bus voltage, δ is the angle associated with V,Y_{ij} is the element of bus admittance matrix, θ is the angle associated with Y_{ij}. Applying Taylor series to equation (3) and (4), the following first order approximation is obtained thus;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{5}$$

In equation (5), bus 1 was taken as the slack bus. The Jacobian matrix gives the linearized relationship between small changes in $\Delta\delta_i$ and voltage magnitude $\Delta V_i$with the small changesin real and reactive power ΔP_i and ΔQ_i, such that the difference between the scheduled and calculated values, known as the power residue (power mismatch) is obtained thus;

$$\Delta {P_i}^{(k)} = P^{sch} - P_i^{(k)} \tag{6}$$

$$\Delta {Q_i}^{(k)} = Q^{sch} - Q_i^{(k)} \tag{7}$$

The new estimate for bus voltages is obtained thus;

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{8}$$

$$V_i^{(k+1)} = \left|V_i^k\right| + \Delta\left|V_i^k\right| \tag{9}$$

The solution of the above equations enables us to identify weak points in the system where the voltage magnitude are less than 0.95 per unit, these weak buses need reactive compensation, for compensated transmission system, equation (4) is modified and is defined by equation (5) below;

$$Q_i - Qd_i + Qc_i = -\sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad i = 1,2,3 \ldots\ldots, n \tag{10}$$

Where Qc_i=additional reactive power support at bus i^{th}, with the power factor of the system raised from 0.85 to 0.96 for compensation purpose, the sizing of additional reactive power needed to raise the voltage at defective buses is obtained using (11) below;

$$Q_c = P\left[\frac{1}{Pf_{(1)}} sin\left(\frac{1}{cos}\left(Pf_{(1)}\right)\right) - \frac{1}{Pf_{(2)}} sin\left(\frac{1}{cos}\left(Pf_{(2)}\right)\right)\right] \tag{11}$$

where P= Real Power for uncompensated system,$Pf_{(1)}$ =Uncompensated system (0.85), $Pf_{(2)}$ =Compensated system (0.96),

The capacitance value required for compensation which will be injected at the defective bus in the power load flow program is given thus;

$$C = \frac{Qc}{2\pi f V^2} \tag{12}$$

Where f= frequency ($50H_Z$) and V= High voltage of 330kV

C. Mathematical Modeling of Load Tap- Changing Transformer into Newton-Raphson Based Load Flow

Load tap changing transformers regulate nodal voltage magnitude by varying automatically the transformer tap ratio under load, the acceptable voltage range limits is given thus;

$$V_{k-min} \le V \le V_{k-max} \tag{13}$$

The tap setting for the LTC transformer range limits is given by;

$$T_{k-min} \le T_k \le V_{k-max} \tag{14}$$

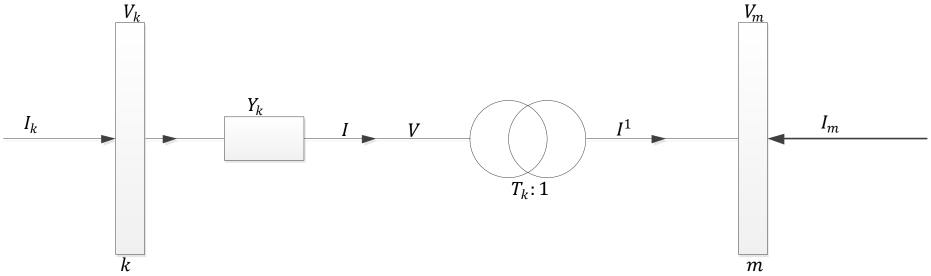

Figure 1 : Simple tap – changing transformer [20]

With the basic assumption that the load tap changer (LTC) controls the nodal voltage magnitude at its sendingend (bus k) of Fig. 1 above, a set oflinearized power flow equations for thenodal power injections equations writing by [20] is given thus;

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \end{bmatrix}^{(i)} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial T_m} T_k & \frac{\partial P_k}{\partial V_m} V_m \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial T_k} T_k & \frac{\partial P_m}{\partial V_m} V_m \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial Q_m} & \frac{\partial Q_k}{\partial T_k} T_k & \frac{\partial Q_k}{\partial V_m} V_m \\ \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_k}{\partial T_k} T_k & \frac{\partial Q_m}{\partial V_m} V_m \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\theta_k \\ \Delta\theta_m \\ \frac{\Delta T_k}{T_k} \\ \frac{\Delta V_m}{V_m} \end{bmatrix} \tag{15}$$

The tap variable T$_k$is adjusted within constraint limits of 0.9 to 1.1 and $V_k$specified the value of voltage magnitude at bus k, at this mode of operation $V_k$is maintained constant at the targetvalue. With the incorporation of Load Tap-Changing Transformer, the active power loss is given by the equation (16);

$$P_{L_{km}} = P_k + P_m \tag{16}$$

The sending voltage magnitude (V_k), the receiving end voltage magnitude (V_m) and the tap ratio T_k are related by the equation (17) ;

$$V_k = \frac{V_m}{T_k}\left(\frac{\cos(\theta_k - \theta_m + \propto)tan\emptyset - \sin(\theta_k - \theta_m + \propto)}{cos\alpha tan\emptyset - sin\alpha}\right) \tag{17}$$

If the power factor angle ($\emptyset$) and the firing angle (α) are assumed to be constant, then equation (17) becomes;

$$V_k = \frac{V_m}{T_k}(\cos(\theta_k - \theta_m) - \sin(\theta_k - \theta_m)) \tag{18}$$

At any time the value of V_k is below the set of voltage binding limits of 0.95p.u to 1.05 p.u, with voltage V_m $constant$,then valueof the tap ratio $T_k$would be increased so as toimprove the voltage magnitude and conversely.

IV. RESULTS AND DISCUSSION

This section shows the results of power flow calculations simulated in MATLAB (R2016b, **Version 9.1**) for 330kVNigerian 24-bus system which has four thermal generating stations (Egbin, Delta, Afam and Sapele) and three hydro stations (Kainji, Jebba and Shiroro) interconnecting various load points. The MATLAB program was run on a portablecomputer with an Intel Core2 Duo (1.8GHz) processor, 2GB RAM memory and MS Windows 8 as an operating system.

The convention of bus with highest generated power (MW) and voltage phase angle of zero degree was adopted and in this case, Bus 1 was taken as the slack bus. The accuracy of $1.000e^{-003}$ was specified in the power flow program, the maximum power mismatch of $3.49553e^{-07}$was obtained and convergence occurred in 5 iterations with shunt compensation while thesolutions converged in 4 iterations with incorporation of LTC transformers. Figure 2below shows the one-line diagram of the case study.

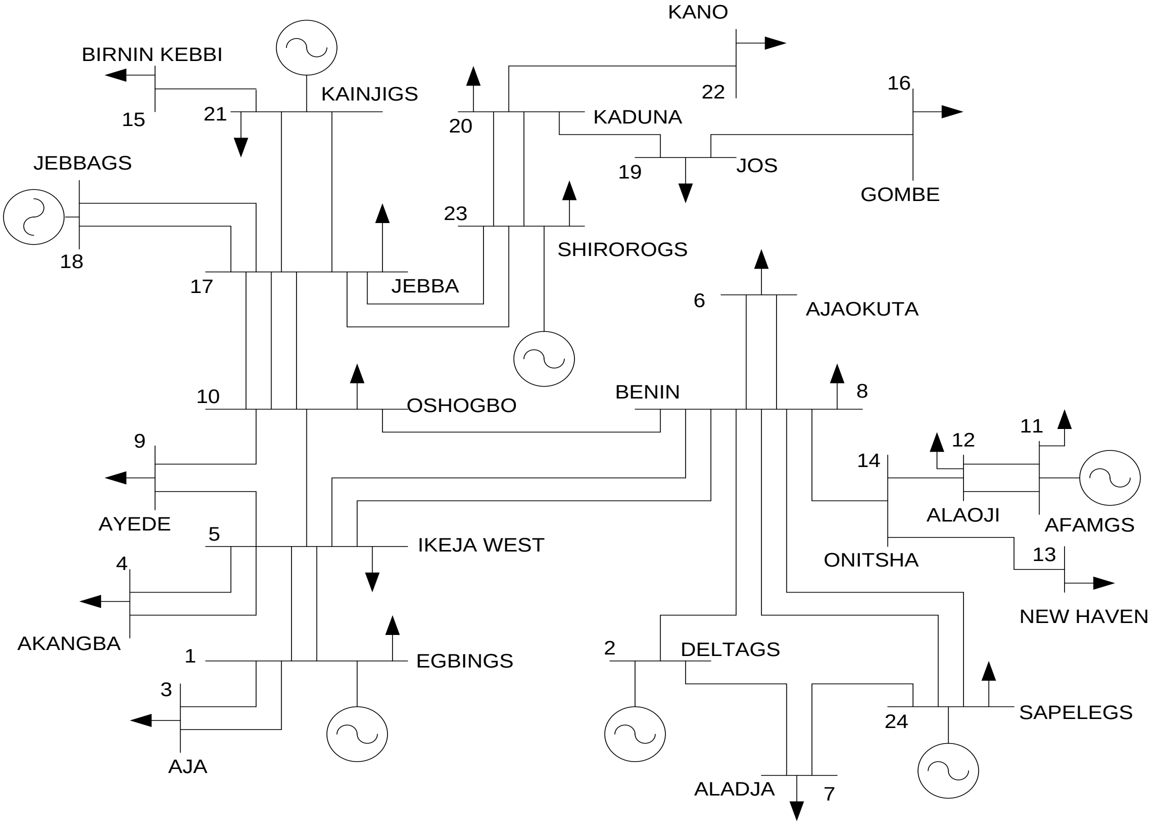

Figure 2: 24-bus 330kV Nigerian transmissionsystem (Source: National Control Centre, Osogbo, PHNC, 2009)

Table 1 below presents the result of the simulation carried out on Nigerian 330kV, 24-bus system using Newton Raphson Load Flow iterative techniques, voltages at the following buses Akangba (4), Ayede (9), New Haven (13), Onitsha (14), Gombe (16), Jos (19) and Kano (22) were found to fall below the minimum acceptable limit of 0.95 p.u., to improve the voltage magnitude at these buses, the following capacitor sizes ($3\mu F$) at bus 4, at bus 9 ($26\ \mu F$), at bus 13 ($17\mu F$), at bus 14 ($16\mu F$), at bus 16 ($12\mu F$), at bus 19 ($7\mu F$) and at bus 22($25\ \mu F$) were installed to inject adequate Mvar needed to raise the voltages within the acceptable ranges of limit as seen in table 2 below. Table 3 shows that with incorporation of LTC transformer of magnitudes 0.950, 0.975, 0.975, 1.09, 1.09 and 1.025 respectively in the line date of Nigerian 330kV, 24-bus grid system, an appreciable improvement in the voltage magnitude of the system were observed as presented Table 4. Table 5 compared LTC transformers and Shunt Capacitors in terms of no of iteration required, total system losses and percentage reduction in total system losses. The system losses before compensation was found to be 86.1331MW, with injection of reactive power via shunt capacitors total system losses reduced to 82.5982MW which about 4% reduction whereas with the incorporation of LTC transformers an appreciable reduction was observed, and the system losses reduced to 81.9865MW which about 5% reduction.

A. Newton-Raphson's Based Power Flow Solutions without Shunt Capacitor Compensation and LTC Transformer Incorporation

Table1: Power flow solution without shunt compensation and LTC transformer

Bus	Voltage	Angle	------Load------		-----Generation-----		Injected
No	**Mag.**	**Degree**	**MW**	**Mvar**	**MW**	**Mvar**	**Mvar**
1	1.050	0.000	68.90	51.70	1483.40	769.01	0.00
2	1.050	-1.066	0.00	0.00	670.00	3.01	0.00
3	1.045	-0.284	274.40	205.80	0.00	0.00	0.00
4	0.948	-5.609	344.70	258.50	0.00	0.00	0.00
5	0.996	-5.159	633.20	474.90	0.00	0.00	0.00
6	1.054	-6.916	13.80	10.30	0.00	0.00	0.00
7	1.046	-2.635	96.50	72.40	0.00	0.00	0.00
8	1.034	-6.556	383.30	287.50	0.00	0.00	0.00
9	0.934	-7.689	275.80	206.80	0.00	0.00	0.00
10	1.026	-4.785	201.20	150.90	0.00	0.00	0.00
11	1.050	-17.192	52.50	39.40	431.00	464.88	0.00
12	1.033	-17.816	427.00	320.20	0.00	0.00	0.00
13	0.929	-18.816	177.90	133.40	0.00	0.00	0.00
14	0.791	-16.010	184.60	138.40	0.00	0.00	0.00
15	1.010	-3.768	114.50	85.90	0.00	0.00	0.00
16	0.875	-31.975	130.60	97.90	0.00	0.00	0.00
17	1.050	-1.409	11.00	8.20	0.00	0.00	0.00
18	1.050	-1.149	0.00	0.00	495.00	-58.89	0.00
19	0.944	-24.431	70.30	52.70	0.00	0.00	0.00
20	1.004	-17.167	193.00	144.70	0.00	0.00	0.00
21	1.050	1.752	7.00	5.20	624.70	-114.67	0.00
22	0.880	-15.453	199.80	149.90	0.00	0.00	0.00
23	1.050	-11.883	320.10	256.10	388.90	480.64	0.00
24	1.050	-5.046	20.60	15.40	190.30	213.41	0.00
Total			**4200.70**	**3166.20**	**4283.30**	**1757.40**	**0.00**

B. Newton-Raphson's Based Power Flow Solutions with Shunt-Capacitors Compensation

Table 2: Power flow solutions with shunt compensation

Bus	Voltage	Angle	------Load------		-----Generation-----		Injected
No	Mag.	Degree	MW	Mvar	MW	Mvar	Mvar
1	1.050	0.000	68.90	51.70	1483.29	744.87	0.00
2	1.050	-1.066	0.00	0.00	670.00	-22.18	0.00
3	1.045	-0.284	274.40	205.80	0.00	0.00	0.00
4	0.948	-5.609	344.70	258.50	0.00	0.00	110.00
5	0.996	-5.158	633.20	474.90	0.00	0.00	0.00
6	1.054	-6.916	13.80	10.30	0.00	0.00	0.00
7	1.046	-2.633	96.50	72.40	0.00	0.00	0.00
8	1.034	-6.556	383.30	287.50	0.00	0.00	0.00
9	0.975	-7.688	275.80	206.80	0.00	0.00	90.00
10	1.026	-4.784	201.20	150.90	0.00	0.00	0.00
11	1.050	-17.177	52.50	39.40	431.00	444.05	0.00
12	1.034	-17.808	427.00	320.20	0.00	0.00	0.00
13	0.999	-18.806	177.90	133.40	0.00	0.00	58.00
14	0.972	-16.004	184.60	138.40	0.00	0.00	50.00
15	1.010	-3.766	114.50	85.90	0.00	0.00	0.00
16	0.975	-31.974	130.60	97.90	0.00	0.00	38.00
17	1.050	-1.408	11.00	8.20	0.00	0.00	0.00
18	1.050	-1.148	0.00	0.00	495.00	-58.95	0.00
19	0.949	-24.430	70.30	52.70	0.00	0.00	20.00
20	1.004	-17.166	193.00	144.70	0.00	0.00	0.00
21	1.050	1.753	7.00	5.20	624.70	-114.67	0.00
22	0.987	-24.875	199.80	149.90	0.00	0.00	25.00
23	1.050	-11.881	320.10	256.10	388.90	480.63	0.00
24	1.050	-5.044	20.60	15.40	190.30	187.58	0.00
Total			**4200.70**	**3166.20**	**4283.19**	**1657.34**	**366.00**

C.Newton-Raphson's Based Power Flow Solutions with Load Tap-Changing Transformer (LTC)

Table 3: Power flow solutions with incorporation of LTC transformer

Bus	**Voltage**	**Angle**	**------Load------**		**---Generation---**		**Injected**
No.	**Mag.**	**Degree**	**MW**	**Mvar**	**MW**	**Mvar**	**Mvar**
1.	1.050	0.000	68.90	51.70	1483.40	769.01	0.00
2.	1.050	-1.066	0.00	0.00	670.00	3.01	0.00
3.	1.045	-0.284	274.40	205.80	0.00	0.00	0.00
4.	0.999	-5.409	344.70	258.50	0.00	0.00	0.00
5.	0.996	-5.159	633.20	474.90	0.00	0.00	0.00
6.	1.054	-6.916	13.80	10.30	0.00	0.00	0.00
7.	1.046	-2.635	96.50	72.40	0.00	0.00	0.00
8.	1.034	-6.556	383.30	287.50	0.00	0.00	0.00
9.	0.978	-7.689	275.80	206.80	0.00	0.00	0.00

10.	1.026	-4.785	201.20	150.90	0.00	0.00	0.00
11.	1.050	-17.192	52.50	39.40	431.00	464.88	0.00
12.	1.033	-17.816	427.00	320.20	0.00	0.00	0.00
13.	1.014	-18.845	177.90	133.40	0.00	0.00	0.00
14.	0.982	-15.013	184.60	138.40	0.00	0.00	0.00
15.	1.010	-3.768	114.50	85.90	0.00	0.00	0.00
16.	0.986	-30.978	130.60	97.90	0.00	0.00	0.00
17.	1.050	-1.409	11.00	8.20	0.00	0.00	0.00
18.	1.050	-1.149	0.00	0.00	495.00	-58.89	0.00
19.	0.985	-23.431	70.30	52.70	0.00	0.00	0.00
20.	1.004	-17.167	193.00	144.70	0.00	0.00	0.00
21.	1.050	1.752	7.00	5.20	624.70	-114.67	0.00
22.	1.027	-22.832	199.80	149.90	0.00	0.00	0.00
23.	1.050	-11.883	320.10	256.10	388.90	480.64	0.00
24.	1.050	-5.046	20.60	15.40	190.30	213.41	0.00
TOTAL			**4200.70**	**3166.20**	**4283**	**1757.40**	**0.00**

D. Result Summary

The summary of the voltage improvement as well as reduction in total system loses caused by theinjected Mvar and LTC transformers incorporation is presented in Table 3 below

Table 4: Shows the Summary of result obtained from the power flow Analysis

Bus No	Bus Name	Magnitude without compensation	Voltage Magnitude with shunt capacitor compensation	Voltage Magnitude with Shunt LTC transformer incorporation	Voltage Angle without compensation	Voltage Angle with Shunt Capacitor Compensation	Voltage Angle with LTC incorporation
1	Egbin	1.050	1.050	1.050	0.000	0.000	0.000
2	Delta	1.050	1.050	1.050	-1.066	-1.063	-1.063
3	Aja	1.045	1.045	1.045	-0.284	-0.284	-0.284
4	Akangba	0.948	0.998	0.999	-5.609	-5.609	-5.404
5	Ikeja-West	0.996	0.996	0.996	-5.159	-5.158	-5.158
6	Ajaokuta	1.054	1.054	1.054	-6.916	-6.914	-6.914
7	Aladija	1.046	1.046	1.046	-2.635	-2.633	-2.633
8	Benin	1.034	1.034	1.034	-6.556	-6.553	-6.453
9	Ayede	0.934	0.975	0.978	-7.689	-7.688	-7.588
10	Oshogbo	1.026	1.026	1.026	-4.785	-4.784	-4.764
11	Afam	1.050	1.050	1.050	-17.192	-17.177	-17.122
12	Alaoja	1.033	1.034	1.033	-17.816	-17.808	-17.808

13	New Haven	0.929	0.999	1.014	-18.816	-18.806	-18.845
14	Onitsha	0.791	0.972	0.982	-16.010	-16.004	-16.001
15	Birnii-Kebbi	1.010	1.010	1.010	-3.768	-3.766	-3.666
16	Gombe	0.875	0.975	0.986	-31.975	-31.974	-30.978
17	Jebba	1.050	1.050	1.050	-1.409	-1.408	-1.408
18	Jebbag	1.050	1.050	1.050	-1.149	-1.148	-1.148
19	Jos	0.944	0.949	0.985	-24.431	-24.430	-24.430
20	Kaduna	1.004	1.004	1.004	-17.167	-17.166	-17.066
21	Kainji	1.050	1.050	1.050	1.752	1.753	1.753
22	Kano	0.880	0.987	1.027	-15.453	-24.875	-22.832
23	Shiroro	1.050	1.050	1.050	-11.883	11.881	11.881
24	Sapele	1.050	1.050	1.050	-5.046	-5.044	-5.003

Table 5: Shows comparison of Shunt Capacitor and Load Tap-Changing Transformer in term of No Iteration Required, Total System Losses and % Reduction in Real Power Loses

	Nigerian 330kV Grid System (without Shunt Capacitor & LTCT)	**Nigerian 330kV Grid System (with Shunt Capacitor Compensation)**	**Nigerian 330kV Grid System(Load Tap-Changing Transformer)**
No of Iterations Required	**10**	**5**	**4**
Total Real Power System Losses (MW)	**86.1331**	**82.5982**	**81.9865**
% Reduction in Total System Losses		**4.1%**	**4.8%**

E. **Graphical Illustrations**

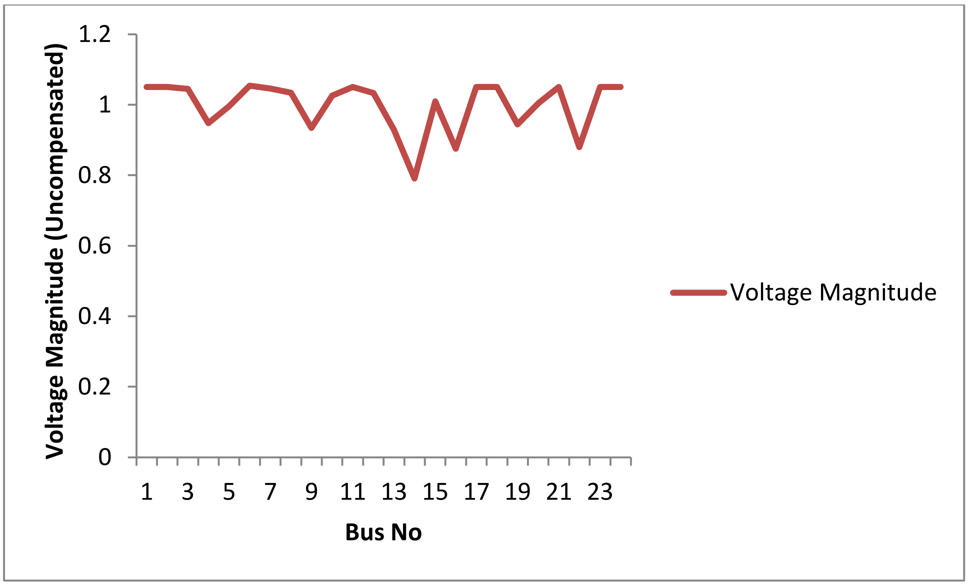

Figure 3: Voltage Magnitude (Uncompensated) versus Bus No

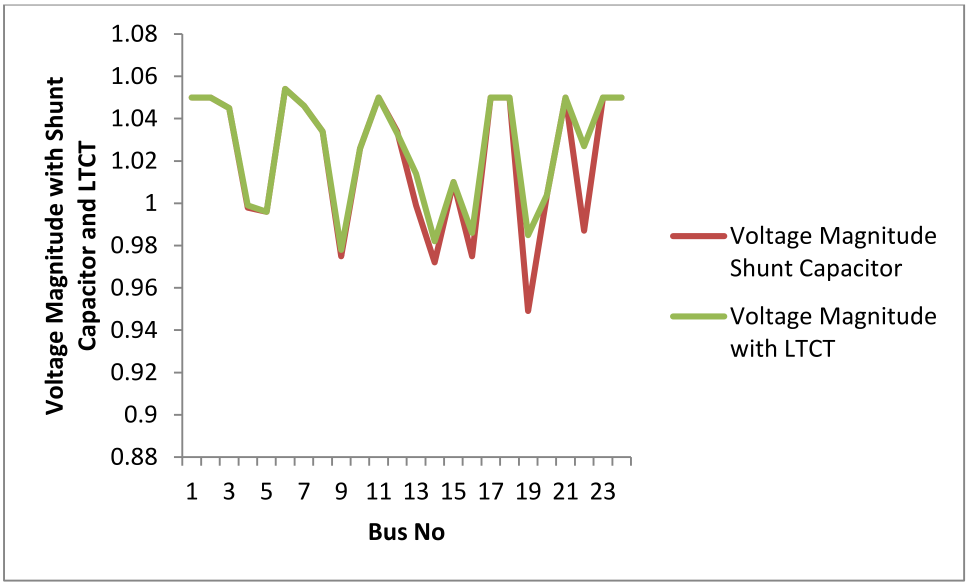

Figure 4: Comparison of voltage magnitude (with Shunt Capacitor injection and LTCT incorporation)

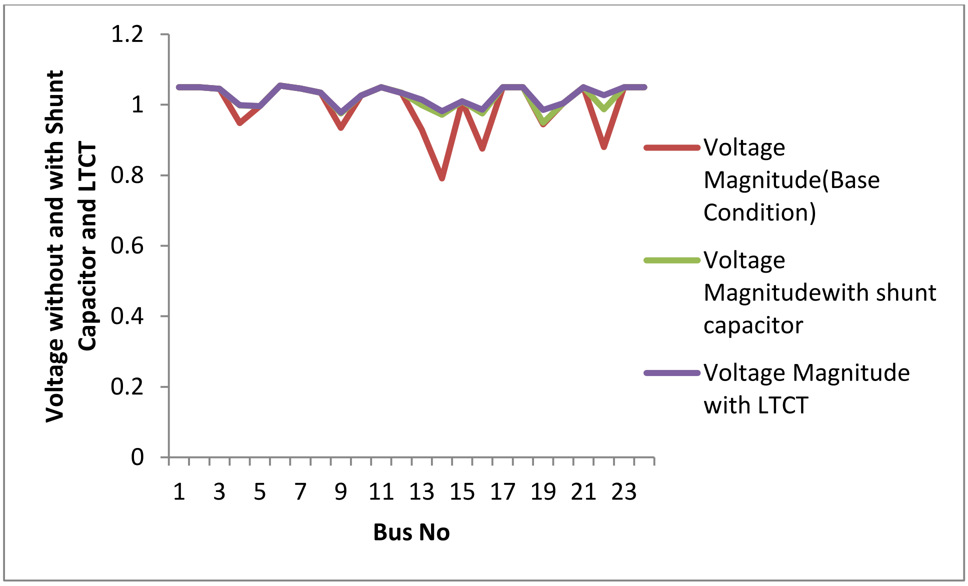

Figure 5: Comparison of voltage magnitude (with and without Shunt Capacitor injection and LTCT incorporation)

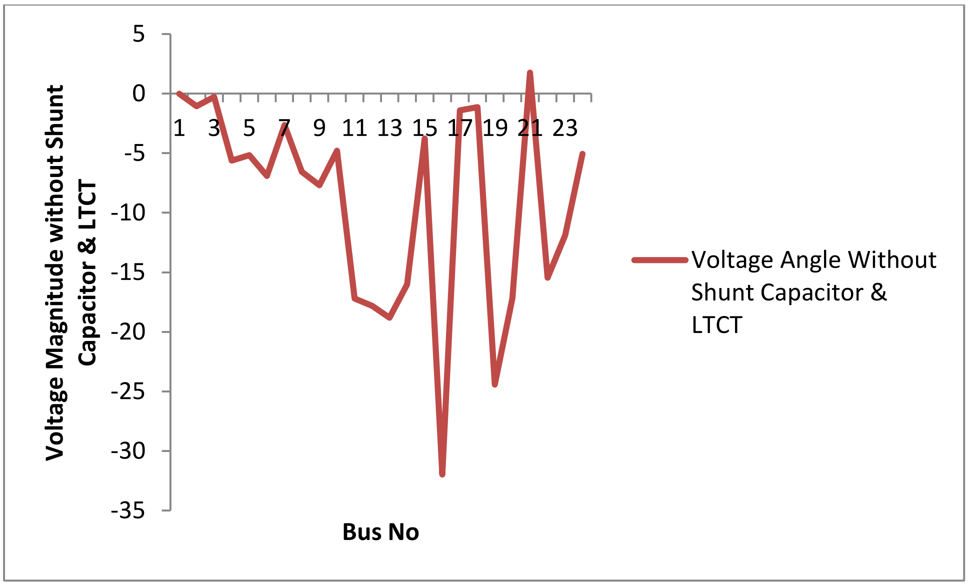

Figure 6: Voltage Angle without Shunt Capacitor and LTCT versus Bus No

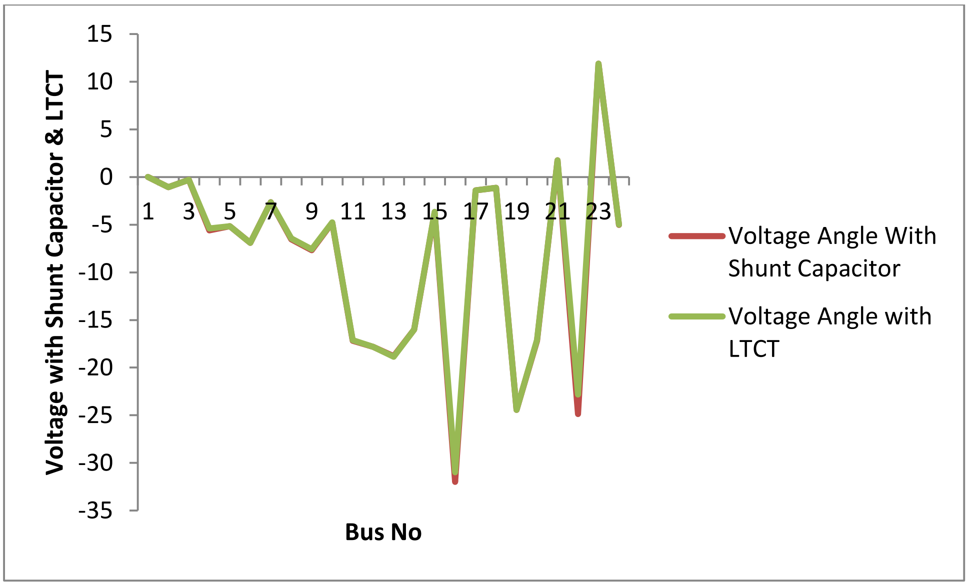

Figure 7: Comparison of voltage angle magnitude (with Shunt Capacitor Injection and LTCT incorporation)

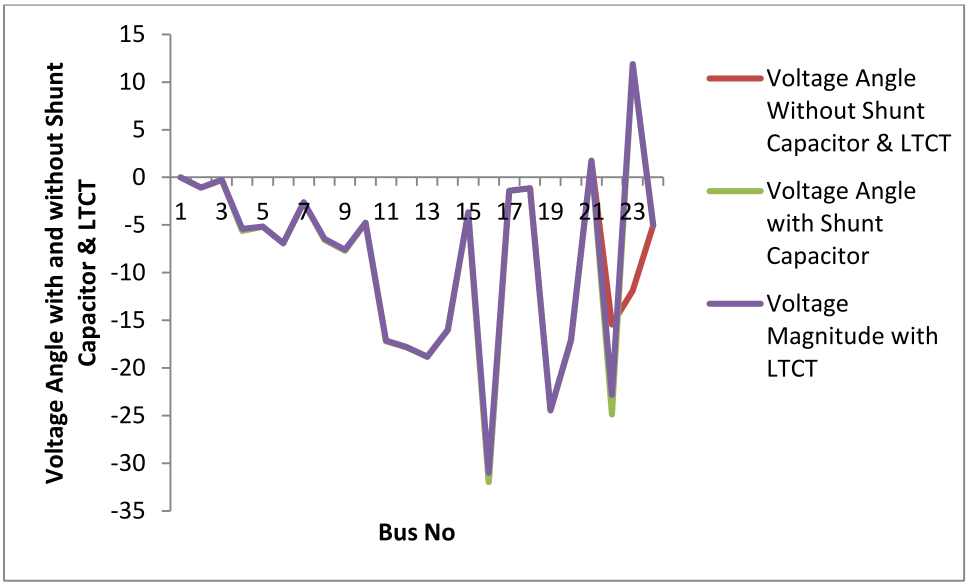

Figure 8: Comparison of voltage angle magnitude (with and without Shunt Capacitor injection and LTCT incorporation)

V. CONCLUSION

Comparative application of discrete controllers (LTCT and Shunt Capacitors) for voltage profile enhancement on Nigerian 330kV, 24-Bus transmission system has been implemented in MATLAB (R2016b, version 9.1). Newton-Raphson iterative techniques was used to carry out theload flow analysis with and without Shunt Capacitor Injection and Load Tap - Changing Transformer incorporation, weak buses with voltage magnitude less than 0.95 p.u wereidentified, an optimum amount of reactive power were injected and tap setting on the line data of the test case corresponding to these weak buses were adjusted within the acceptable range limits so as to raise the voltage magnitude at these buses within acceptable range of limits of 0.95-1.05 p.u.

The study shows that with shunt capacitors injection, convergence was achieved in 5 iterations but with LTC transformer convergence was achieved in 4 iterations, the total power system losses with shunt capacitor injection was found to be 82.2826MWwhile with LTC transformer, the total system losses reduced appreciably to 81.9865MW. Incorporation of LTCT gives a better improvement on system voltage profile compared with the improvement observed with shunt capacitor injection. Also, the bus voltage angle improved appreciably with LTCT than with shunt capacitor injection.

Therefore, applying load tap changing transformers (LTC) were found to be more reasonable in term of system voltage profile enhancement and reduction in total power losses than reactive power compensation using shunt-type capacitor injection.

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