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Electric Power Transmission Enhancement: A Case of Nigerian Electric Power Grid

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Abstract Increase in economic activities resulting from increase in population and social advancement has led to increase in electrical energy demands. This has increased the burdens on the existing transmission assets and in some cases, has caused the loading of the transmission assets beyond their design limits with consequent reduction in power quality and power outages in extreme cases. Many techniques have been developed to enhance the capabilities of the power grids. This paper looks into these techniques with the view to exploring their applicability to the Nigerian 330KV electric power grid, towards seeking ways to enhancing the performance of the grid for better asset utilization. A typical transmission line in the grid was modeled to assess its strengths and weaknesses. Enhancement techniques were then applied to assess their impacts on the line.

Keywords: *power transmission, reactive power, active power, voltage profile, line transfer capability*

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1. Introduction

Electricity markets deregulations have made electric energy more like a commodity that is bought in bulk from one market location and sold in another and from one country to another. These deregulations, coupled with increase in energy demand due to increasing population and economic activities, have in some cases resulted in over utilization of the transmission system as some of the transmission lines are stressed beyond their design limits.

The increase in demand on the transmission system has made some of them to be loaded more than their power transfer capacities and this has in some places reduced the quality of power delivered and in some other cases, resulted in cascading overloads with consequent power outages [1]. Because of these, researchers are working round the clock to devise means of extending the power transfer capacities of the transmission lines while maintaining the quality of power delivered through them. Technically, the limitation on power transfer capacity on a transmission line can always be removed by addition of new transmission capacity, but the economic, political and environmental considerations in building of new transmission facilities have made this option not always desirable [2]. Meanwhile, an important aspect of the contract terms for these inter regional and international power purchases is that the transmission system be adequate for the power evacuation [3,4].

Currently, in Nigeria, the previously government-owned power generation and distribution companies have been privatized. It is expected that this privatization will result in better management of these utility companies resulting in increased generation and more efficient power distribution and revenue collection [5]. It is a fact that the success of the privatized system still depends on the effectiveness of the transmission system.

This work seeks to evaluate the strength of the Nigerian electric power grid as well as ways to enhance the performances of the transmission lines in the grid with the aim of achieving better utilization of the available transmission assets.

The rest of the paper is organized as follows. Section II outlines the major concepts in transmission line performances. Section III presents Nigerian electric power grid and the methodology. Results and observations are presented in section IV, while conclusions are made in section V.

2. Transmission Line Performance

2.1. Line Parameters

All transmission lines in a power system are made to transport energy from power generation stations to distribution stations. Hence, they exhibit the electrical properties of resistance, inductance, capacitance, and conductance. The resistance is due to the nature of the conductor while inductance and capacitance are due to the effects of magnetic and electric field around the conductor. These parameters form the basis for the development of transmission line models used in power system studies. The shunt conductance accounts for leakage current which flows across insulators and ionized pathways in the air.

The leakage currents are negligible compared to the current flowing in the transmission lines and may be neglected [6].

2.2. Power Flow through Lines

The aim of power lines is to effect power transmission from one bus to another or from one grid to another. Transmission lines are built either in single circuit or double circuit lines (for higher capacities). Power flow through a line is determined by the voltage magnitudes of the two buses connected by the line, the line impedance and the difference in angles of the voltages of the two buses. When double circuit (parallel line) is involved, the fact that current flows through the line of least impedance path can also bring about an imbalance in the flow of power and this can cause an overloading of one line of the circuit in some cases as the other line operates quite below its power rating [7].

For a simple 2-bus transmission system shown in Figure 1, the power flow through the line is represented by equations 1-2, where $\delta = \delta_1 - \delta_2$.

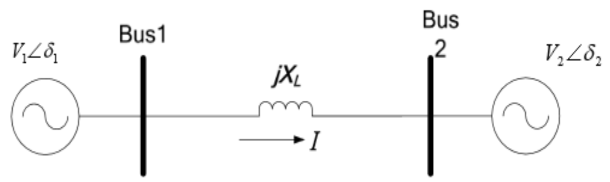

Figure 1. Simplified model of a power transmission system

$$P_2 = \frac{V_1 V_2 \sin\delta}{X_L} \tag{1}$$

$$Q_2 = \frac{V_2 \left(V_2 - V_1 \cos\delta\right)}{X_L} \tag{2}$$

$$V = f(P,Q) \tag{3}$$

Equations above indicate that the active and reactive power/current flow can be regulated by controlling the voltages, phase angles and line impedance of the transmission system. Real power transfer can be increased by increasing the line voltage, reducing the line reactance or by increasing δ. From (1), the active power flow will reach the maximum when the difference in phase angles δ is 90º but in practice, a small angle difference, between 35º to 45º, is used to keep the system stable from the transient and dynamic oscillations [8]. Also, from equation (2), reactive power at any bus is dependent on the voltage drop along the line, such that reactive power increases with increase in voltage difference between the two buses. As a result of (1) and (2), the voltage at the receiving–end of the line becomes a function of the active and reactive power flow through the line as given in (3). For effective operation of a transmission line, these transmission parameters are kept under control. Power flow balance is achieved in a parallel transmission line using series compensation or phase shifting transformers [9].

2.3. Surge Impedance Loading

The surge impedance loading (SIL) of a transmission line is the MW loading of the transmission line at which a natural reactive power balance occurs. It is simply the MW loading at a unity power factor at which the lines MVar usage is equal the line's MVar production, causing reactive powers to cancel out. SIL is given in equation form as:

$$\text{SIL} = \frac{(V_{Lrated})^2}{Z_c} \tag{4}$$

Where Z_C is the characteristic impedance or surge impedance of the line.

The concept of SIL is important in transmission line studies because it sets the theoretical limit for stable operation (power delivery) for very long lines and indicates where the reactive requirements of the line are small.

2.4. Line Loadability

There is always an inherent trade-off between increasing utilization of the grid and security of grid's operation. Loadability of a transmission line is defined as the optimum power transfer capability of a transmission line under a specified set of operating criteria. Many research works have been carried out on the improvement of transmission transfer capability with a variety of operation constraints, such as stability, voltage security and thermal limits [10]. St. Clair curve [11] provides a simple means for estimating power transfer capabilities of transmission lines. It concerns three limiting factors: thermal limit, voltage drop limit and angular stability limit which usually affects short, medium and long transmission lines respectively. Voltage limit and stability limit fall below thermal limit. Compensation can be used to modify the natural parameters of transmission lines and to increase loadability of long lines toward their thermal limit.

2.5. Transmission Systems Enhancement Strategies

Several methods which could be used to enhance the performances of transmission lines have been reported in [9,12,13], which include:

1. **Installation of New Transmission Line:** This is usually the first option that comes to mind whenever a transmission line is limited in the amount of power it can transmit, so as to alleviate overloading by providing additional paths for power flow. It is beneficial by increasing the reliability of the transmission system. However, it has to pass through economic, political and environmental hurdles.

2. **Reconductoring Transmission Line/Terminal Equipment Replacements:** A line can be reconductored with a larger conductor with more power-carrying capability if the original transmission line conductor is inadequate to carry expected power flows, provided that the transmission line towers do not need to be significantly altered to support the heavier conductor. In addition, some terminal equipment may need to be upgraded to match the desired rating.

3. **Conversion from single circuit to double circuit:** This involves making necessary modifications to the existing transmission towers and adding a second transmission line to the structure. This option extensively reduces the line impedance and increases current-carrying

capacity of the line, thereby increasing power transmission capacity of the line.

4. **Voltage Upgrade:** Another option is to increase the operating voltage of the transmission line, such as upgrading the voltage from 132 kV to 330 kV. In this instance, for example, the nominal rating of the line maybe drastically increased while using the same conductor. This type of improvement may require upgrading the transmission towers to meet National Electric Safety Code (NESC) clearance levels. In addition, the switching stations and substations must also be upgraded with higher voltage circuit breakers, switches, transformers, and other related equipment.

5. **Reactive Power Compensation**: Addition of reactive power compensation devices (especially FACTS devices) in the form of series compensation, shunt compensation or the combination of the two, (depending on the nature of the line and its identified deficiency and need) to the transmission line is also another means of enhancing the performances of a transmission line. The addition of compensation modifies the electrical impedance of the line and therefore increases the power flows across the line. This can be an effective and economical means of increasing the transmission capability as a whole, by taking advantage of transmission lines that are not loaded to their thermal limits.

6. **Phase Shifting:** Inequality in line impedances of a double circuit transmission line can bring about imbalance in load sharing between the circuits of the line: a situation where one circuit suffers overload while the other is under loaded. This is because electric current naturally flows through the path of least impedance. Addition of phase shifting device in the line helps to regulate and to better control the power flows on the system to optimize the existing transmission capability by distributing the power flows across the transmission lines.

3. Nigerian 330kv Power Grid; A Test Case

The Nigerian 330kv power transmission grid is made up of 28 buses connected by a total of 5523.8km length of transmission lines. The grid, shown in Figure 2, is characterized by poor voltage profile in most parts of the network, inadequate dispatch and control infrastructure, radial and fragile grid network, inadequate available generation capacity, and inadequate or total absence of spinning reserve [14]. The grid is marred by incessant voltage and frequency instability issues [15], leading to load curtailments. These instabilities have often resulted in total system collapse such that the grid experienced an average of thirty-one (31) system collapse per year for the period between years 2000-2014 [16,17].

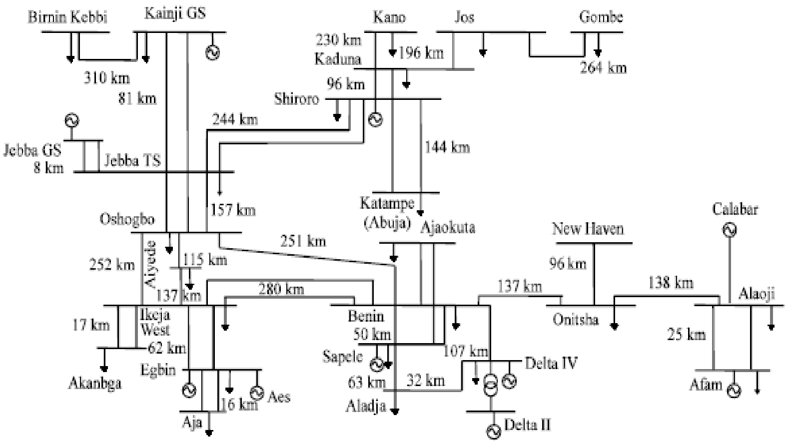

Figure 2. One-line diagram of Nigerian 330kv grid

Table 1. Different Generation levels and violations observed [18]

S/N	GENERATION LEVELS	GENERATION		DEMAND		LOSSES		No. of Voltage Violations (-/+5%)	Thermal Rating Violation (<760MVA)
		P_G (MW)	Q_G (MVAR)	P_D (MW)	Q_D (MVAR)	P_L (MW)	Q_L (MVAR)		
1	Base Case at 2284MW Generation	2284.50	-549.26	2230.60	1394.10	54.04	-1989.58	1	No violation
2	Generation Increase to 3063.71MW	3036.71	92.16	3000.00	1875.00	63.50	-1782.86	1	No violation
3	Generation Increase to 4114.38MW	4114.38	974.10	4054.80	2534.50	59.75	-1530.36	1	No violation
4	Generation Increase to 4500MW	4505.00	1867.03	4300.00	2687.50	22.14	-766.11	13	1 violation
5	Generation Increase to 4711.77MW	4711.77	2051.14	4500.00	2812.50	225.60	-713.20	13	1 violation
6	Generation Increase to 7290.09MW	7290.09	4719.21	6768.40	4230.25	650.12	1948.19	12	5 violations
7	Generation Increase to 10024.51MW	10024.51	7829.00	9000.00	5625.00	1173.62	3902.43	16	7 violations

The power grid delivers low power quality while transmitting the present available generating capacity of 4949MW [17], and should deliver even lower power quality while transmitting the current peak demand forecast of 12800MW. Analysis [18] carried out on the grid (Table 1) shows that the grid, at its present state, cannot stably transmit the current power demand of the grid and will be much less capable if the generation becomes sufficient, which formed the motivation for this present work.

This study was carried out using the line, which connects Onitsha and New Haven substations. The line was constructed and commissioned in the year 1982. It has a total length of 96km. The line is composed of two bundled ACSR 350 mm^2, 54/7 BISON conductors per phase with horizontal configuration. The parameters of the line are given in Table 2 below. The performance of the line was evaluated to deduce ways to enhance it for better utilization.

Table 2. Parameters of the transmission line

Parameter	Value
Line Voltage, V	330KV
Line Length, ℓ	96km
Line Inductance, L	1.06302mH/km/phase
Line Capacitance, C	0.01076μF/km/phase
Line Resistance, R	0.033698Ω/km/phase
Line Conductance, G	0.00 Siemens/km/phase (assumed)
Current Capacity, I	1360A/phase
Line Power Rating	760MVA

Two-port network (Figure 3) model of transmission lines relates the sending-end quantities with the receiving-end quantities using ABCD constant as shown in (5)

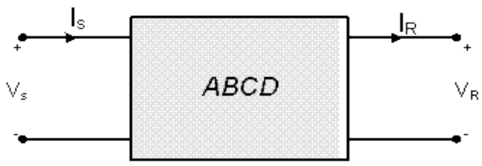

Figure 3. Two-port representation of a transmission line

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}. \qquad (5)$$

The transmission line was modeled and simulated at different loading levels. The simulation was carried out in MATLAB platform using power system analysis toolbox provided in [6]. The sending-end to receiving-end relationships were observed at the different loading levels to determine the voltage drop characteristics of the line. St. Clair's curve was also generated for the line, which indicated the thermal and the stability limits of the line. Different enhancement strategies were then applied to find out whether they could affect the line performances.

4. Observations and Discussion

4.1. Open-Line Characteristics

Figure 4 shows the voltage profile of the line while open-circuited at the receiving end (i.e. at no load when the line is being charged). The figure shows that there is a rise in the voltage of the line at the receiving end. Though it is still within tolerance limit (330kv$\pm$5%) for the line under study, it can rise above the limit for a longer line as depicted in Figure 3b where the same line design was used but the length was extended to 500km. In the case of a longer line, (Figure 4(b)), the receiving end voltage has even risen to 383KV. It also shows that the voltage level of Figure 4(a) was brought back to 330KV after the line has been compensated with a shunt reactor of reactance XLsh = 6206.21Ω which consumed 19.46Mvar from the line, while that of 4(b) was brought back to 330KV after it was compensated with a shunt reactor of reactance XLsh=1164.66Ω which consumed 93.72Mvar from the line.

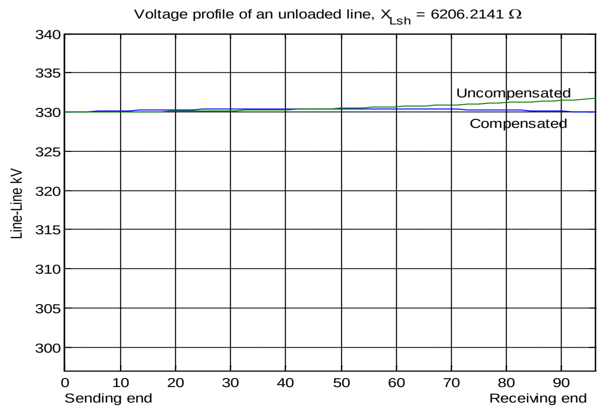

Figure 4. (a) open-line voltage profile (normal length)

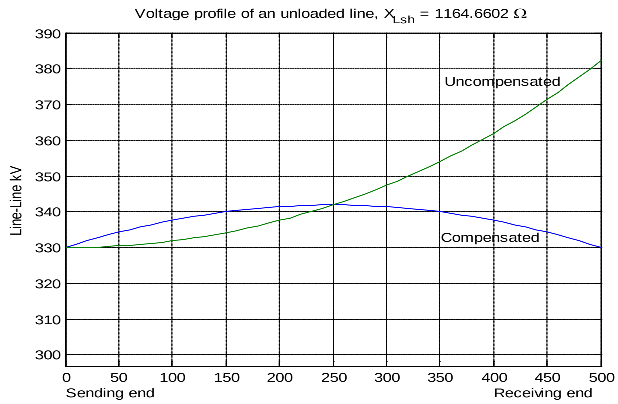

Figure 4. (b) open-line voltage profile (500km)

4.2. Line's Voltage Profile

It was observed, after subjecting the line to varying sending-end power levels, that the voltage at the receiving end kept decreasing as the sending-end power increased until at about 185MW when voltage violation occurred. 185MW at 0.8 p.f. is equivalent to 231MVA, which is far below the line rating of 760MVA. It was also observed in Table 3 that as the load increases, current through the line increases with a consequent increase in power (I^2R) loss on the line. Percentage voltage regulation also increases with increase in power transmitted, and the efficiency of the line decreases. Figure 5 presents the voltage profiles of the line at different loading levels. It shows that for lines of about 80km and above, the receiving-end voltage becomes totally unusable if the line is loaded to its rated capacity. This means that the lines in the system cannot be utilized to their rated capacities especially considering the radial nature of the grid network.

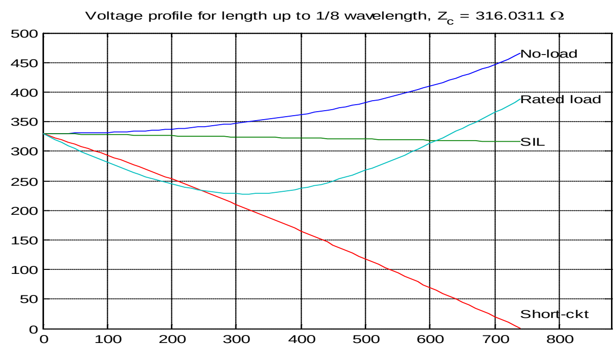

Figure 5. The line's voltage profiles

Table 3. Sending-end to receiving-end characteristics

Sending-end		Recieiving-end				Losses		V. Reg. %	Eff. %
Voltage VS(KV)	Power Ps(MW)	voltage V_R (KV)	I_R (A)	P_R (MW)	Q_R (MVAR)	P_L (MW)	Q_L (MVAR)		
330	50.00	324.80	153.90	49.83	70.62	0.17	-33.12	2.24	99.67
330	75.00	322.20	206.20	74.67	87.53	0.33	-31.28	2.97	99.56
330	100.00	320.20	259.30	99.45	103.87	0.55	-28.87	3.61	99.45
330	125.00	318.20	312.90	124.17	119.63	0.83	-25.88	4.26	99.33
330	150.00	316.20	366.70	148.83	134.83	1.17	-22.33	4.91	99.22
330	175.00	314.20	420.70	173.43	149.45	1.57	-18.20	5.57	99.11
330	200.00	312.30	474.70	197.98	163.50	2.02	-13.50	6.22	98.99
330	225.00	310.40	528.80	222.47	176.99	2.53	-8.24	6.88	98.88
330	250.00	308.50	583.00	246.90	189.90	3.10	-2.40	7.54	98.76
330	275.00	306.60	637.20	271.27	202.23	3.73	4.02	8.20	98.65
330	300.00	304.70	691.50	295.59	214.00	4.41	11.00	8.87	99.52
330	325.00	302.90	745.70	319.85	225.20	5.15	18.55	9.53	98.42
330	350.00	301.03	800.00	344.05	235.83	5.95	26.67	10.20	98.30
330	375.00	299.20	854.30	368.19	245.88	6.81	35.37	10.86	98.18
330	400.00	297.40	908.60	392.27	255.36	7.73	44.63	11.53	98.07
330	425.00	295.70	962.90	416.30	264.28	8.70	54.47	12.20	97.95
330	450.00	293.90	1017.20	440.27	272.63	9.73	64.88	12.86	97.84
330	475.00	292.20	1071.60	464.18	280.40	10.82	75.85	13.53	97.72
330	500.00	290.50	1125.90	488.03	287.60	11.97	87.40	14.20	97.61
330	525.00	288.80	1180.20	511.83	294.22	13.17	99.52	14.86	97.49
330	550.00	287.10	1234.60	535.56	300.29	14.44	112.22	15.53	97.38
330	575.00	285.50	1288.90	559.24	305.77	15.76	125.48	16.19	97.26
330	600.00	283.89	1343.30	582.87	310.69	17.14	139.31	16.85	97.14

4.3. Line transfer capability

St. Clair curve on Figure 6 has in display, the theoretical stability limit, practical stability limit and thermal limit of the test case transmission line. It can be seen that the power transfer by the line is not affected by any of the stability limits being that the line is not long enough.

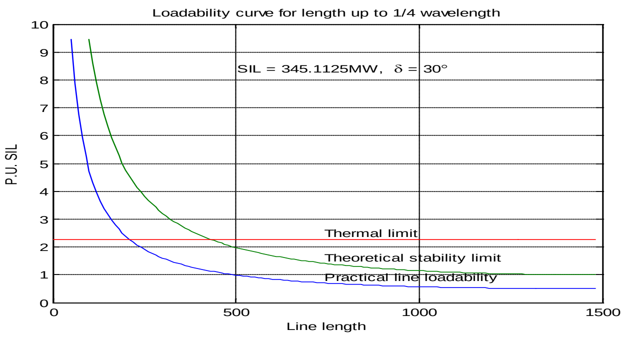

Figure 6. The line's loadability curve at 330KV operating voltage

Worthy of note also is the fact that the thermal limit of the line at 330KV voltage level is at 2.3P.U. SIL, which is at 794MW, far above the line standard rating. Hence, the power transfer capability of the line is not limited by either stability limits or thermal limits. If the length of the same line is increased to above 500km, stability of the line will limit its power transfer capability to a point less than its SIL, and then, enhancements would be needed to get the line to transmit a reasonable amount of power.

4.4. Effect of Line Reconductoring

A case of changing the sizes of the conductors of the transmission line was examined to determine its effects. The conductors of the line were replaced with the same conductor size but three conductors bundle. Increasing the bundle size increases the geometric size of the conductor thereby affecting both the resistive and the magnetic characteristics of the conductor. It was observed that reconductoring the line did not show any significant effect on the voltage profile and the angular stability of the line as shown in Figure 7. The effect observed was in the thermal characteristics, where the SIL became 388MW and the thermal limit rose to 3p.u.SIL which is 1164MW.

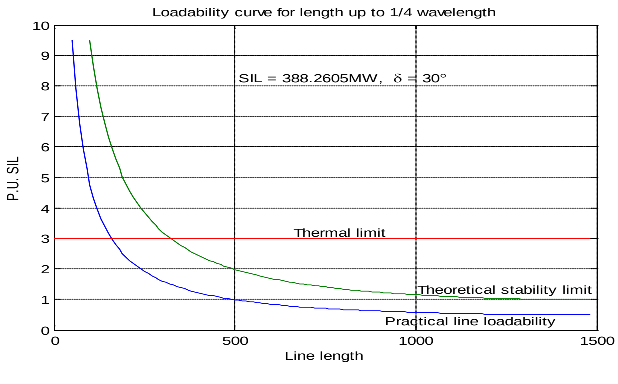

Figure 7. The line's loadability curve for reconductored line at 330KV

4.5. Effect of Increase in Voltage Level

Figure 8(a) and Figure 8(b) show the effects on the line when the line voltage was increased to 450KV and 500KV respectively. It can be seen that at 450, the SIL has increased to 641.738MW and the thermal limit is at about 1.7 P.U. SIL (about 1090MW), and at 500KV, the SIL has increased to 792.269MW and thermal limit is at 1.5 P.U. SIL (about 1188.4MW). It is also worth noting that the line is still able to transfer reasonable amount of power at 500km length even with the effects of stability limits.

These show that upgrading the voltage level can increase line loadability and increase asset utilization.

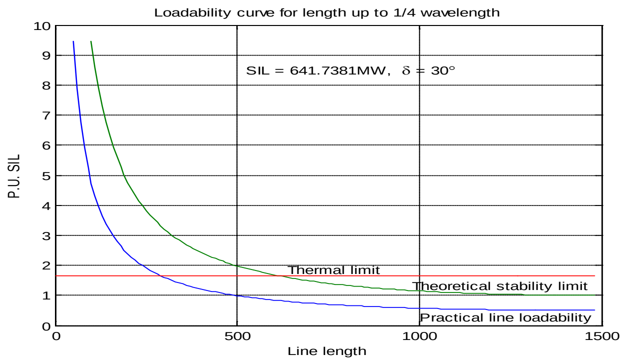

Figure 8a. Loadability at 450kv voltage level

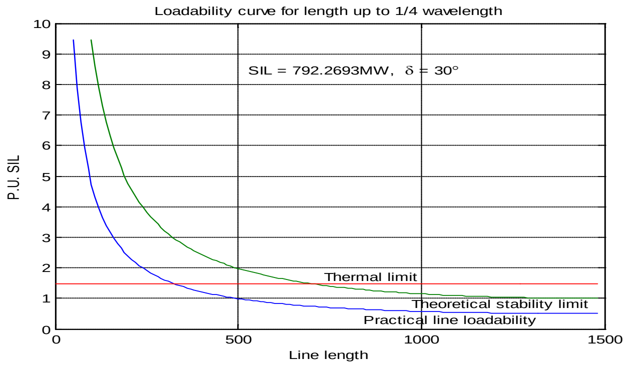

Figure 8b. Loadability at 500kv voltage level

4.6. Effect of Compensation

Table 4. Effects of compensation on the transmission line

VS/VR	Recieiving-end			Losses		V. Reg. (%)	Eff. (%)	Reguired Capacitor Spec.		
	IR (A)	PR (MW)	QR (MVAR)	PL (MW)	QL (MVAR)			Ohm	µ-Farad	MVAR
330.00	89.79	49.83	12.29	0.08	-34.63	0.52	99.85	1867.05	1.42	58.33
330.00	131.65	74.67	9.32	0.17	-33.71	0.52	99.77	1392.50	1.91	78.20
330.00	174.33	99.45	6.18	0.30	-32.43	0.52	99.70	1114.75	2.38	97.69
330.00	217.30	124.17	2.86	0.47	-30.77	0.52	99.63	932.57	2.84	116.77
330.00	260.39	148.83	-0.64	0.67	-28.76	0.52	99.55	803.84	3.30	135.47
330.00	303.52	173.43	-4.32	0.91	-26.39	0.52	99.48	708.20	3.75	153.77
330.00	346.67	197.98	-8.18	1.18	-23.65	0.52	99.41	634.34	4.18	171.68
330.00	389.81	222.47	-12.20	1.50	-20.56	0.52	99.33	575.60	4.61	189.19
330.00	432.92	246.90	-16.41	1.84	-17.11	0.52	99.26	527.86	5.03	206.31
330.00	475.99	271.27	-20.78	2.23	-13.31	0.52	99.19	488.31	5.43	223.01
330.00	519.04	295.59	-25.33	2.64	-9.15	0.52	99.11	455.01	5.83	239.33
330.00	562.06	319.85	-30.06	3.10	-4.63	0.52	99.04	426.63	6.22	255.26
330.00	605.03	344.05	-34.95	3.59	0.23	0.52	98.97	402.17	6.60	270.78
330.00	647.96	368.19	-40.02	4.12	5.45	0.52	98.90	380.90	6.96	285.90
330.00	690.85	392.27	-45.26	4.68	11.02	0.52	98.82	402.41	6.59	270.62
330.00	733.71	416.30	-50.67	5.23	16.94	0.52	98.75	345.77	7.67	314.95
330.00	776.53	440.27	-56.25	5.90	23.20	0.52	98.68	331.13	8.01	328.88
330.00	819.32	464.18	-62.00	6.57	29.82	0.52	98.61	318.05	8.34	344.40
330.00	862.06	488.03	-67.92	7.27	36.78	0.52	98.53	306.32	8.66	355.52
330.00	904.78	511.83	-74.01	8.00	44.10	0.52	98.46	295.74	8.97	368.23
330.00	947.45	535.56	-80.26	8.78	51.75	0.52	98.39	286.16	9.27	380.55
330.00	990.10	559.24	-86.69	9.58	59.75	0.52	98.32	277.48	9.56	392.46
330.00	1032.93	582.87	-93.28	10.43	68.10	0.52	98.24	269.57	9.84	403.97

Deploying shunt reactors to the unloaded line was able to restore the receiving-end voltage to an acceptable level, while shunt capacitor deployed at the receiving-end of the loaded line and varied according to the reactive power demand was able to maintain the receiving-end voltage at an acceptable level. Table 4 summarizes the effects of compensation on the transmission line. It shows the specifications of shunt capacitors required to restore the receiving-end voltage shown in Table 3 back to the 330KV. It can also be observed that the line losses reduced and the voltage regulation and efficiency of the line improved as a result of the compensation. This shows that by placing FACTS devices at the receiving-end of the line, the desired compensation at any load level can automatically applied and keep the voltage at a desired level.

5. Conclusion

The existing Nigerian national power grid is being underutilized due mainly to the radial nature of the network and lack of voltage control devices in the network. The lines in the 330KV transmission network are not limited by stability limits (the longest being the Kainji-Brinin kebbi line of 310km), and they are not limited by thermal limit but their limitations are their voltage drop levels, which cause load curtailment and limit the lines at load levels far below their thermal limits. There is need for investment into expanding and strengthening the power grid.

Reconductoring, as a power grid strengthening strategy, may not yield a reasonable improvement on the grid in question. Though transmission at Ultra High Voltage (UHV) levels can create rooms for more power evacuation, it requires much investment in changing terminal and substation equipment, and amendments of transmission towers. Hence, this may not be a feasible option at the moment but having UHV transmission backbone is still desirable for effective power evacuation.

The power grid should be fortified with voltage control equipment especially in the form of FACTS devices located at strategic points on the grid to control voltage sags and to increase the power handling capacity of the grid thereby enhancing utilization of the grid.

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