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Voltage Stability Improvement by Inclusion of Parallel Transmission Lines: A Case Study of Western Kenya Region

Richard Ochieng Obumba[1]

Department of Mechanical and Manufacturing
Engineering
University of Nairobi
Nairobi, Kenya
rickobumba@gmail.com[1]

Peter Moses Musau, Abraham Nyete[2]

Department of Electrical and Information
Engineering
University of Nairobi
Nairobi, Kenya

pemosmusa@uonbi.ac.ke[2]

***Abstract* — An integrated power system should provide stable and reliable power supply in any given economy. Western Kenya Region (WKR) has experienced voltage instabilities caused by inadequate transmission line infrastructure. The remedy adopted by Kenya Power is Under Voltage Load Shedding This paper proposes inclusion of parallel transmission lines to lower overall impedance and improve voltage stability and power transfer capability. The region's transmission system was modelled on an IEEE 39 Bus System and simulated using Digsilent Powerfactory software. The results revealed that parallel inclusion of transmission network significantly improved voltage levels and reduced loading of the main transmission lines into the region. The minimum bus voltage improved by up to 6.2%, whereas power transfer capability improved by an average of 42.09%. A Benefit/Cost Analysis qualified implementation of the proposed project to be economically viable. Due to increased loading on transmission lines, addition of Capacitor banks or suitable Flexible Alternating Current Transmission System devices at the buses with the lowest voltages would be recommended.**

Keywords—Voltage Stability, IEEE 39 Bus System, Transmission Lines.

I. Introduction

A tremendous growth of population has been on the rise, but increased availability of power has not been synchronous with this advancement. Maintaining voltage levels for stability purposes is important because deviating voltage values may result in malfunction or enormous damage of critical electrical equipment [1]. Voltage instability may be caused by failure of generation stations due to diminished reactive support. It is imperative for system controllers to maintain voltage levels within the range of 0.95p.u ≤ V ≤ 1. 05p.u, but more important to ensure the voltages are maintained at higher levels, because the probability of having a voltage collapse will be decreased [2]. Voltages are generally high during off-peak and low during peak periods [3]. This paper seeks to address the challenge of voltage stability by ensuring that Under Voltage Load Shedding scheme is avoided as a voltage stability mechanism. The research intends to reveal the possibility of availing power at peak periods, whilst retaining sustainable voltage levels.

II. Literature Review

A. *Transmission Systems for Voltage Improvement*

Power system stability indicates the capability of a power system to regain a state of equilibrium after being subjected to a physical disruption, with maximum binding of variables to maintain system integrity [4].

Figure 1 is a representation of a simple radial transmission system, depicting the power, current and voltage at the receiving end. These parameters are represented as functions of load demand. The parameters of importance are generated power (P_R), reactive power injected (Q_I) and most importantly, receiving end Voltage (V_R) [5].

In a two terminal transmission system with a source voltage, E_S, series impedance Z_{LN} and load Z_{LD}, the current, I, flowing through the network is given by the relation:

$$I = \frac{1}{\sqrt{F}} \frac{E_S}{Z_{LN}} \qquad (1)$$

where F is a constant, given by

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right) Cos(\theta - \emptyset)$$

Receiving end voltage is given by the relation:

$$V_R = Z_{LD}.I = \frac{Z_{LD}}{\sqrt{F}} \frac{E_S}{Z_{LN}} \qquad (2)$$

The power at the load is therefore expressed as

$$P_R = V_R.I.Cos\emptyset = \left[\frac{Z_{LD}}{\sqrt{F}} \frac{E_S}{Z_{LN}}\right].\left[\frac{1}{\sqrt{F}} \frac{E_S}{Z_{LN}}\right] Cos\emptyset$$

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$$P_R = \left(\frac{Z_{LD}}{F}\right)\left(\frac{E_S}{Z_{LN}}\right)^2 Cos\emptyset \qquad (3)$$

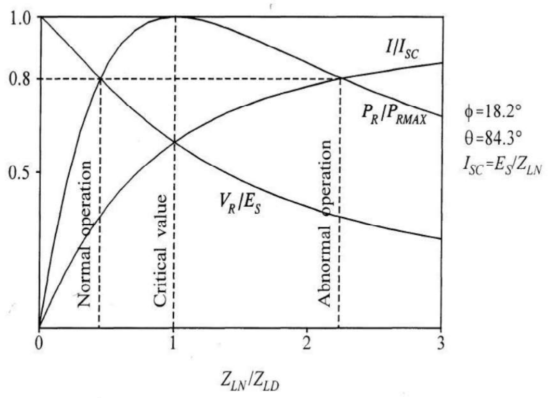

Figure 1: Simple Radial System [5]

Parallel transmission lowers the line impedance, Z_{LN}, to increase the voltage for stability purposes. From the graph in Figure 1, the value of Z_{LN} should be less than Z_{LD}, which decreases gradually as well, but due to increase in load demand. Construction of Parallel transmission lines has been considered preferable in this research. The coupling in Transmission lines is important and should therefore be considered when calculating series impedance and shunt admittance.

Some of the solutions necessary for ensuring voltage collapse is prevented are as follows [5]:

i) Use of reactive power compensation devices.
ii) Proper coordination of protection and control devices with respect to the system needs.
iii) Control of transformer tap changing.
iv) Under Voltage Load Shedding.
v) Automatic network Voltage control.

Instead of constructing new transmission lines, Flexible AC Transmission Systems (FACTS) can be installed onto the existing transmission lines, either in series or shunt, to alter transmission voltage levels [6].

B. *Previous Works*

Several researchers in the past who explored Voltage stability opined that FACTS devices and Distribution Generation (DG) can be used to stabilize voltage levels of a power system. The closest research work was done by I. Kitta et al (2019) [7], who used Load flow simulation software to obtain the voltages and power losses in six scenarios. The first scenario involved simulation of the existing conditions without any additions. The second and third scenario involved addition of 275kV and 150 kV, respectively. Scenario 4, 5 and 6 included 150kV transmission line and varying capacitor banks on different buses. In scenario 4, there was a 20 MVar at the sending end, 20 MVar at the receiving end for scenario 5 and 10 MVar on both the sending and receiving ends in scenario 6. Out of the 6 scenarios, scenario 4 had the highest-highest bus voltage, whereas scenario 2 had the highest-lowest bus voltage. The previous research however did not address the issue of loadability on transmission lines.

C. *Benefit/Cost Analysis*

The Benefit/Cost ratio which is beneficial towards public sector projects is a tool that was adopted in this paper to evaluate the economic viability of pursuing the proposed transmission projects [8]. The Benefit/Cost ratio is expressed as shown in equation (4)

$$B/C = \frac{benefits - disbenefits}{costs} \qquad (4)$$

The total cost of construction of the project was calculated and tabulated as shown in Table 1. When converting the total value from Kenya shillings to U.S Dollars at a rate of 102 Kenya shilling per Dollar, the value becomes \$94,446,072.93.

Table 1: Cost of Constructing proposed Transmission lines and Resettlement [10]

Transmission Line	**Length (KMS)**	**Transmission Line Cost per KM (MUSD) - Double Circuit Line**	**Wayleaves Cost per KM (MUSD)**	**Exchange Rate per Dollar**	**Total Cost (Kshs)**
Olkaria - Naivasha	21.9	0.156	0.178	106	775,347,600.00
Naivasha - Lanet	69.4	0.156	0.178	106	2,457,037,600.00
Lanet - Soilo	15.1	0.156	0.178	106	534,600,400.00
Soilo - Makutano	54.5	0.156	0.178	106	1,929,518,000.00
Makutano - Lessos	54.4	0.156	0.178	106	1,925,977,600.00
Lessos - Muhoroni	56.1	0.078	0.178	106	1,522,329,600.00
Resettlement					488,688,639.00
TOTAL					**9,633,499,439.00**

Where the benefits include the unshaded energy cost added to the energy not paid after decommissioning Muhoroni Gas Turbine. A total load of 5,482.12 MWh of power in WKR was shed in 2018. The rate of unserved energy in KPLC according to the KPLC rates of Economic Analysis of transmission Lines is 1.5 U. S. Dollars. This means that the average energy that could have been saved in 2018 if the proposed project had been implemented was 5,482.12 MWh = 5,482,120 kWh. Total cost of energy saved in U. S. Dollars was $5{,}482{,}120 \times 1.5 = \$12{,}334{,}770.$ Assuming this value as average, then the total cost of energy saved for 5 years would be $61,673,850. The cost of increased losses due to the proposed transmission lines based on KPLC rates was therefore given by: -

$$\begin{aligned} Cost\ of\ Energy\ Losses &= Energy\ loss\ difference\ in\ kW \\ &\times LRMC\ in \frac{USD}{kWh} \times LLF \\ &\times 24\ hours\ a\ day \\ &\times 365\ days\ a\ year\ \times 5\ years \end{aligned}$$

$$Cost\ of\ Energy\ Losses = 1{,}339.756kW \times \frac{0.2773USD}{kWh} \times 0.553 \times 24\ hours\ a\ day\ \times 365\ days\ a\ year \times 5 = \$8{,}998{,}597.50 \qquad (5)$$

According to KPLC's financial statements, the total energy purchased for financial years 2016/2017 and 2017/2018 were 108MW and 65.5MW respectively [9]. The energy that was purchased in the calendar year 2018 was 53,776,000kWh. The merit order average cost of energy for Muhoroni GT was 40.314 Kenya shillings per kWh according to the merit order in Appendix M. The total cost of energy was therefore calculated and found to be 2,167,925,664 Kenya shillings, which is equivalent to $106,270,865 at an exchange rate of Ksh. 102 per dollar for 5 years. The B/C analysis over a period of 5 years was therefore found to be

$$B/C = \frac{\$61{,}673{,}850.+\$106{,}270{,}865-\$8{,}998{,}597.50}{\$94{,}446{,}072.93} = 1.68 \qquad (6)$$

The B/C analysis was calculated to give a result greater than 1, indicating that implementation of the project would be economically viable. Capacity charges have not been included due to confidentiality of the information. If Muhoroni power plant capacity charges to be paid to KenGen per year in the PPA were included in the calculation, then implementation of the proposed project would be more viable.

III. PROJECT SIMULATION

A. *Methodology*

Figure 2 shows the block diagram of the Western Kenya Region (WKR).

The research was based on two different schedules of excitation, where each schedule had 6 diverse scenarios. The first 4 scenarios were based on the existing infrastructure and electrical components, whereas the last 2 scenarios were based on introduced parallel transmission lines. The 2 schedules were as follows:

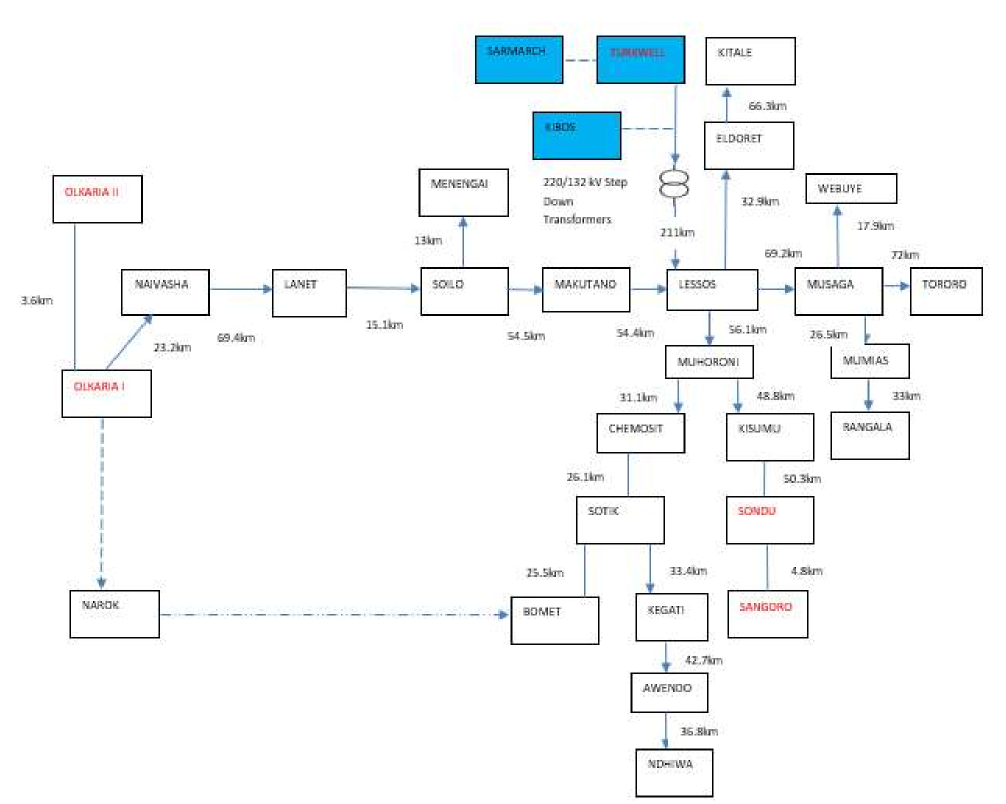

Figure 2: WKR Transmission Network Block Diagram

Schedule 1

Schedule 1 had energy generation connected to the grid from Olkaria 1, Turkwell, Uganda interconnector (Tororo), Sondu and Sang'oro Power stations. The energy from Olkaria 1 contains a mix of energy from Nairobi's grid, and energy generated from Olkaria as well. The simulation gave results and loading of the transmission lines were tabulated in Table 2, whereas bus voltages were tabulated in Table 3.

Schedule 2

Schedule 2 represented generation from Olkaria 1, Turkwell, Sondu and Sang'oro. In this case, power was not being dispatched from Uganda interconnector (Tororo). The simulation gave results and loading of the transmission lines were tabulated in Table 4, whereas bus voltages were tabulated in Table 5.

B. Simulation Results and Discussion

The two schedules were simulated, and results tabulated as shown in Table 2 to Table 5. Table 2 and Table 3 displayed the loading and voltage results for schedule 1 whereas Table 4 and Table 5 displayed the loading and voltage results for schedule 2.

Table 2: Loading of Transmission Lines for Schedule 1

No	**BUSES**	**Transmission Lines**	**Capacitors and Inductors Switched Switched off (Current Status)**	**Capacitors and Inductors Switched Switched on (Current Status)**	**Capacitors switched on; Inductors switched off (Current Status)**	**Capacitors switched off; Inductors switched on (Current Status)**	**Capacitors and Inductors Switched Switched off (Additional parallel lines)**	**Capacitors Switched on (Additional parallel lines)**
1	BUS 32 TO BUS 10	Olkaria 1 - Naivasha	91.2%	83.8%	78.4%	97.6%	34.1%	28.3%
2	BUS 10 TO BUS 13	Naivasha - Lanet	66.0%	60.9%	58.4%	68.9%	36.9%	30.7%
3	BUS 13 TO BUS 14	Lanet - Soilo	45.2%	45.4%	42.4%	48.5%	27.6%	24.1%
4	BUS 14 TO BUS 15	Soilo - Makutano	34.5%	31.9%	28.2%	35.2%	22.0%	18.1%
5	BUS 15 TO BUS 16	Makutano - Lessos	24.3%	24.4%	23.5%	25.9%	17.3%	15.2%
6	BUS 16 TO BUS 21	Lessos - Muhoroni	106.4%	106.6%	104.1%	106.6%	53.4%	51.5%
7	BUS 22 TO BUS 23	Chemosit - Kegati	75.7%	65.7%	65.1%	76.3%	75.2%	64.7%

The results in Table 2 indicated improved loadability whereas Table 3 indicated voltage stability in the region after introducing parallel transmission lines. Additional load could still be accommodated in the network. Bus 23 was also analysed and tabulated, because it revealed that it experienced the lowest voltage in the entire bus system representing Western Kenya Region. The highest loading established prior to additional lines was 106.6% whereas the highest loading for the same section after simulating additional lines became 53.4%. This was a significant improvement in terms of transmission line loading.

The lowest voltage before adding transmission lines was 122.2kV (0.926 per unit) whereas the lowest voltage value after introducing transmission lines was 124.0kV (0.939 per unit). Comparing these values to the lowest acceptable per unit voltage level of 0.94, then it was evident that the additional transmission lines improved the voltages to desirable levels, including bus 23 which experienced the lowest voltages in all cases. Figure 3 shows the Voltage profile bar graph of all the scenarios under schedule 1.

Table 3: Busbar Voltages for Schedule 1 in kV

No	Buses	Transmission Sub Stations	Capacitors and Inductors Switched off (Current Status)	Capacitors and Inductors Switched on (Current Status)	Capacitors switched on; Inductors switched off (Current Status)	Capacitors switched off; Inductors switched on (Current Status)	Capacitors and Inductors Switched off (Additional parallel lines)	Capacitors Switched on (Additional parallel lines)
1	BUS 32	Olkaria 1	132.0	132.0	132.0	132.0	132.0	132.0
2	BUS 10	Naivasha	129.9	130.2	130.4	129..7	132.1	131.4
3	BUS 13	Lanet	129.8	130.1	130.3	129.6	131.1	131.3
4	BUS 14	Soilo	129.7	129.9	130.2	129.4	131.0	131.2
5	BUS 15	Makutano	128.5	128.8	129.3	128.0	130.0	130.5
6	BUS 16	Lessos	128.9	129.1	129.9	128.1	129.7	130.5
7	BUS 21	Muhoroni	128.8	129.0	129.9	128.0	129.7	130.5
8	BUS 23	Kegati	123.0	124.6	125.9	122.2	124.0	126.2

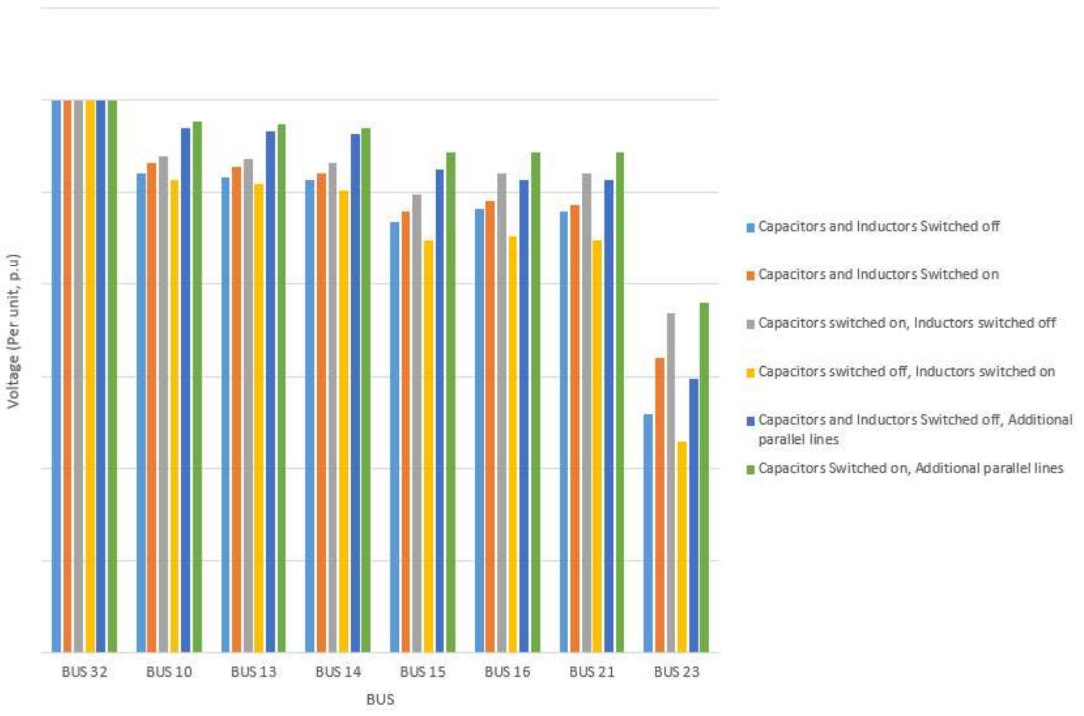

Figure 3: Schedule 1 Voltage Profile Bar Graph

Table 4: Loading of Transmission Lines for Schedule 2

No	**Buses**	**Transmission Lines**	**Capacitors and Inductors Switched off (Current Status)**	**Capacitors and Inductors Switched on (Current Status)**	**Capacitors switched on; Inductors switched off (Current Status)**	**Capacitors switched off; Inductors switched on (Current Status)**	**Capacitors and Inductors Switched off (Additional parallel lines)**	**Capacitors Switched on (Additional parallel lines)**
1	BUS 32 TO BUS 10	Olkaria 1 - Naivasha	163.9%	163.2%	154.0%	175.5%	55.8%	51.7%
2	BUS 10 TO BUS 13	Naivasha - Lanet	104.7%	103.1%	98.4%	110.6%	59.5%	55.1%
3	BUS 13 TO BUS 14	Lanet - Soilo	82.3%	84.2%	79.0%	88.2%	48.5%	45.6%
4	BUS 14 TO BUS 15	Soilo - Makutano	66.0%	68.0%	62.9%	72.0%	40.5%	37.7%
5	BUS 15 TO BUS 16	Makutano - Lessos	23.9%	25.3%	22.8%	29.0%	19.1%	16.8%
6	BUS 16 TO BUS 21	Lessos - Muhoroni	110.5%	123.2%	113.0%	117.4%	53.4%	53.5%
7	BUS 22 TO BUS 23	Chemosit - Kegati	78.0%	68.7%	67.0%	79.6%	76.5%	65.8%

Table 5: Busbar Voltages for Schedule 2 in kV

No	**Buses**	**Transmission Sub Stations**	**Capacitors and Inductors Switched off (Current Status)**	**Capacitors and Inductors Switched on (Current Status)**	**Capacitors switched on; Inductors switched off (Current Status)**	**Capacitors switched off; Inductors switched on (Current Status)**	**Capacitors and Inductors Switched off (Additional parallel lines)**	**Capacitors Switched on (Additional parallel lines)**
1	BUS 32	Olkaria 1	132.0	132.0	132.0	132.0	132.0	132.0
2	BUS 10	Naivasha	129.6	129.6	130.2	129.0	131.1	131.3
3	BUS 13	Lanet	129.4	129.5	130.1	128.9	131	131.3
4	BUS 14	Soilo	129.2	129.2	129.9	128.6	130.9	131.1
5	BUS 15	Makutano	126.7	126.5	127.8	125.3	129.0	129.7
6	BUS 16	Lessos	125.5	124.9	127.2	123.2	127.7	128.9
7	BUS 21	Muhoroni	125.4	124.9	127.2	123.2	127.7	128.9
8	BUS 23	Kegati	119.5	120.2	122.7	117.1	121.9	124.4

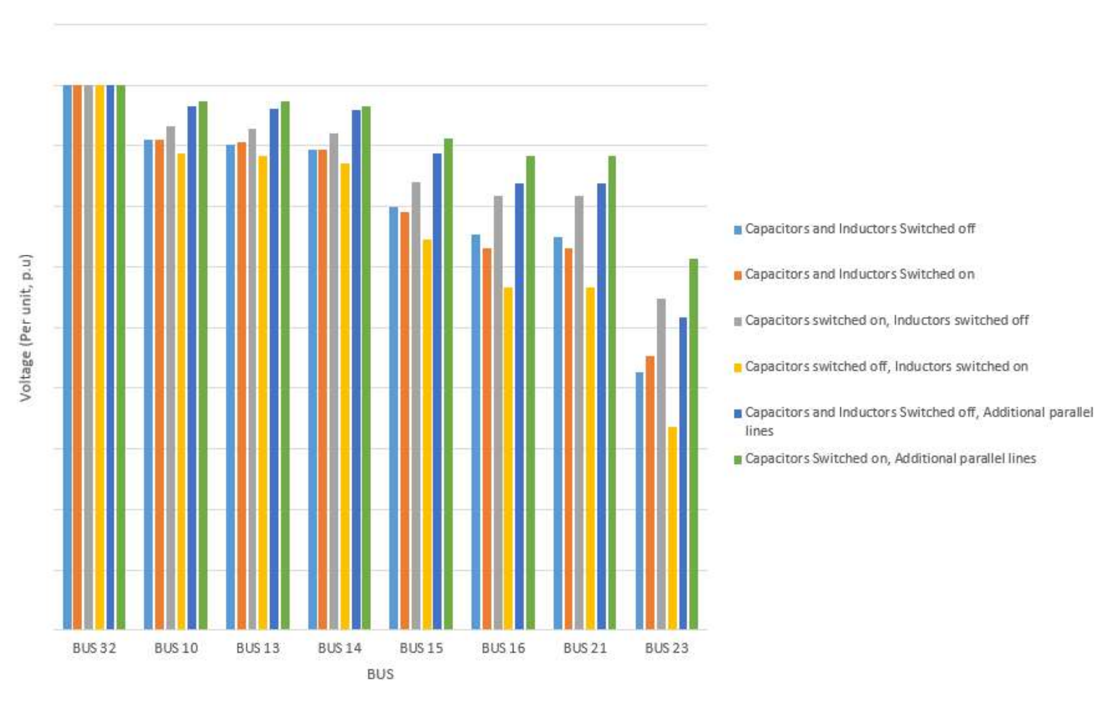

***Figure 4**: Schedule 2 Voltage Profile Bar Graph*

Loading of the transmission lines was very high in every scenario of Table 4, except for the two scenarios whose transmission lines were added. These two scenarios had reduced loading percentages of less than 100%. This therefore meant that additional load could still be accommodated in the network. Only one scenario in Table 4 was in adherence to the required voltage levels. This was the scenario where the additional parallel lines with capacitor banks switched on were simulated. Voltage levels got to as low as 117.1kV (0.887 per unit) before including the proposed transmission lines. The lowest value of voltage obtained after adding the transmission lines was 121.9kV (0.923 per unit). Both values were below the required threshold of 0.94 per unit. Figure 4 is a depiction the Voltage profile bar graph of all the scenarios under schedule 2, based on the buses under study. Simulation results in Table 4 shows that there was massive improvement in loading of all the transmission lines under consideration when parallel lines were added. Moreover, none of the additions depicted loading of over 80%. The highest transmission loading was 76.5%, which can still transfer additional load. Only two scenarios accomplished desirable voltage levels, with reference to Bus 23 which experienced the lowest voltages at any given schedule. The lowest voltage before adding transmission lines was 121.2kV (0.918 per unit) whereas the lowest voltage value after introducing transmission lines was 123.3kV (0.934 per unit). These values were both below the required threshold of 0.94 per unit. Additional transmission lines relatively improved the voltages of the buses under consideration as shown in Table 5. Some voltages after addition of parallel transmission lines indicated were still below the admissible threshold. The results in all the scenarios showed that switching on capacitors at maximum loads raise voltages to be significantly within range.

C. *Validation*

According to I. Kitta et al (2019) [7], insertion of 275kV transmission network in one scenario and 150kV in another showed a very slight difference of 0.0046pu in voltage profile improvement between the two. Scenario 2 which inserted 275kV improved to 0.9611pu, whereas scenario 3 which inserted 150kV improved to 0.9565pu. This slight difference justifies the advantage of proposing in this research a 132kV transmission line as opposed to a 400kV or 220kV which certainly costs more. The minimum bus voltage of the author's research had a slight improvement of 0.0152pu, whereas the improvement obtained from the lowest bus in schedule 2 was a high of 0.0553pu.

IV. CONCLUSION AND RECOMMENDATION FOR FURTHER WORK

In conclusion, the research work showed that the introduction of parallel transmission lines improved the voltage profile of the WKR when attempting to meet maximum demand. The improved per unit voltages were improved from values as low as 0.887pu to 0.942pu (6.2%), and values as high as 0.988pu to 0.996pu (0.81%). The simulation results also revealed the bottlenecks experienced in terms of loadability when attempting to meet peak demand. Prior to additional transmission lines, the results showed that some line sections in WKR were loaded above 100%. The average loading of the transmission lines in scenarios 1, 2, 3 and 4 was 75.99%, whereas average loading of transmission lines after introduction of transmission lines in scenarios 5 and 6 was 42.09%. This significant reduction improved the loadability of the transmission lines by 44.61%. This paper recommends that inclusion of transmission lines tend to improve power transfer capability and augment voltage levels. The lowest voltage at bus 23 was within range, but not as near as perfect. Placement of specific transmission lines and strategic capacitor banks and/or inductors therefore need to be studied for optimization of the region's voltage profile and loading of the transmission lines in WKR. Based on the simulation, a minimum of 130MVAr may be considered for installation at Bus 23 to ensure voltage is boosted to at least 1.003pu. Further studies on installing the best and economically viable FACTS device ought to be done as well. Installation of a FACTS device at bus 23 would boost the ever-suppressed voltages as seen in both schedules. Further studies ought to be done to ensure that transfer of power is optimized, and voltage at the distribution level is not affected.

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