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Mitigation of Technical Losses in Ghana's Transmission Network using Optimal Capacitor Bank Allocation Technique

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Strictly as per the compliance and regulations of :

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Kingsley Bediako Owusu [α], John Kojo Annan [σ], Emmanuel Effah [ρ] & Fred Kwame Tweneboah-Koduah [ω]

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I. Introduction

Availability of electrical power has been the most powerful engine facilitating economic, industrial and social developments of many countries. As the population of the world continues to grow rapidly and countries become more industrialized, the need for electrical energy also becomes more paramount.

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Ghana Grid Company Limited (GRIDCo), a single and independent entity, is responsible for the economic dispatch and transmission of electricity from the generating company's sub- sections (Volta River Authority's (VRA) sections; Akosombo and Kpong hydroelectric power plant, Bui hydroelectric power plant, Takoradi Thermal Power Plant (Aboadze) etc.) to bulk customers, which include, Electricity Company of Ghana (ECG), Northern Electricity Distribution Company (NED), the Mines, smelter companies, textile companies etc. The electric power is transmitted by means of transmission lines, which deliver bulk power from the generating stations to the various load centers. However, a significant percentage of the generated power is lost in the transmission process. Available data indicates that, as at the end of 2013, the technical losses at GRIDCo were 4.49 % of the power generated, which is an appreciable deviation from the minimum allowable percentage loss of 3.5% [1]. These transmission losses often result in low and reduced power to the final consumer, and consequently, amount to increased operational costs contributed by the huge penalties in the tunes of millions of Cedis, which is paid monthly to these generating stations by GRIDCo.

II. Literature Review

The electric power system comprises of three major parts, namely, generation, transmission and distribution systems. The generation system is mainly responsible for the conversion of energy resources into electrical power by alternators or generators [2].

After electrical power is generated, the transmission systems transmit the bulk power to various load centers through transmission lines. The distribution system then conveys the electrical power to consumers. Figure 1 shows the basic structure of the electric power system of Ghana.

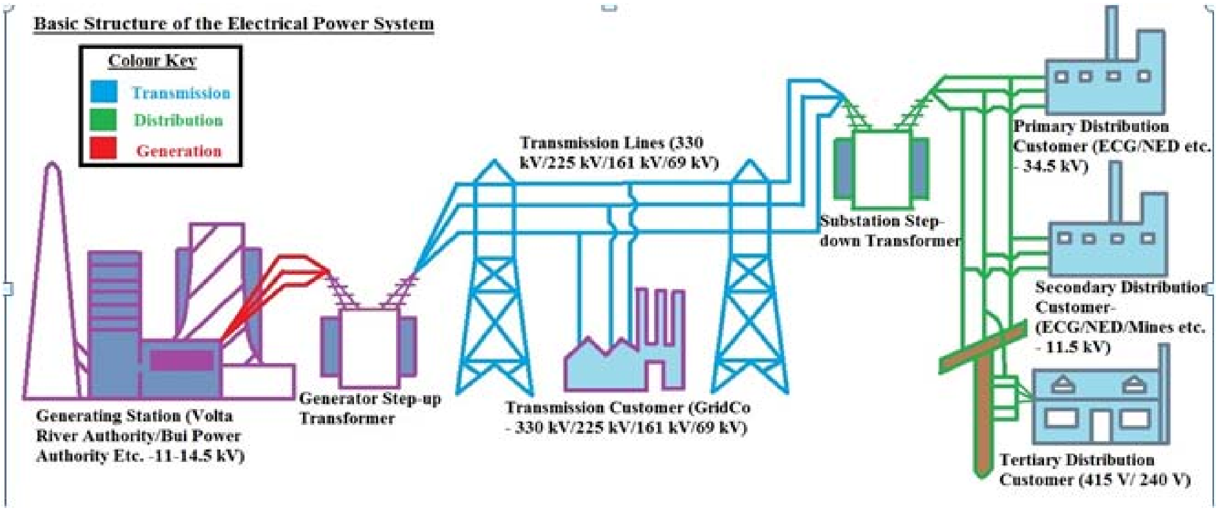

Figure 1 : Basic Structure of the Electric Power System of Ghana

Transmission lines are usually modeled by means of parameters for the purpose of system analysis. A given transmission line can be represented by its resistance, inductance, capacitance and leakage reactance. The leakage reactance is usually neglected [3].

A lot of losses occur during the process of transmitting energy or electrical power from generating stations to various load centers. A loss refers to a reduction in an expected value. The total losses encountered in transmitting electrical power through a system are basically termed as transmission losses. Mitigation of losses is a necessity in electric power system, so [4] investigated into the type of voltage distribution system which will result in lower losses by comparing an existing low voltage distribution system to a proposed high voltage distribution system. The study proved that conversion to high voltage results in a number of advantages such as increase in energy saving, a reduction in system losses, a more reliable system and subsequent reduction in power outages. Mathematically, transmission losses can be defined as the difference between the amount of electricity entering the grid network from the generation section or import from neighbouring transmission grids and the export to the transmission grids or the electricity leaving the grid for consumption. i.e. Power loss = power transmitted from network – power received by consumers as shown in equation 1 below.

$$P_{Loss} = P_T - P_R \quad (1)$$

Generally, the losses occurring in transmission systems are classified as non-technical (commercial) or technical losses. [5] further classified non-technical losses as: unauthorized line tapping and meter tampering, unauthorized line diversions and illegal connections, Inadequacies and inaccuracies in meter reading, Inaccurate customer electricity billing, Non-payment of electricity bills, Inaccurate estimation of non-metered supplies such as public lighting, agricultural consumption, rail traction etc.

Technical losses are losses due to energy dissipation in the conductors and equipment used for transmission, transformation, sub-transmission and distribution of electrical power [6]. Due to the negative impacts technical losses have on the net power to consumers, [7] investigated into technical losses in Hatyai of Provincial Electricity Authority (PEA) to devise a strategy for mitigating it.

Technical losses are inherent in the system and can be reduced to an optimum level. [8] delved into the optimum location of STATCOM devices in long transmission line as a means of acquiring maximum power system transient stability improvement, in order to reduce transmission losses. [9] also developed a mathematical model for analysing losses along electric power transmission lines using ohmic and corona losses. Their study revealed that transmitting electric power at a very low current and at an operating voltage close to the critical disruptive voltage minimises losses and further recommended large spacing between conductors compared to their area.

All the above related works investigated into either finding strategies to minimize transmission losses or comparing two network systems to ascertain which one was less prone to transmission losses. None delved into investigating a power flow analysis to determine how much reactive power compensation is required to be deployed on a transmission network to reduce these transmission losses. This is what this study seeks to address.

These losses result in forfeiture of capital. Available Data shows that GridCo incurred the total losses of GH¢ 44,099,588.43 ($12,599,882.41) and GH¢ 49,017,455.75 ($14,004,987.36) for 2012 and 2013 respectively [1].

III. Transmission Losses Realized by GRIDCo

Data was collected on the monthly energy losses recorded between January 2012 and December 2013, as well as the cost of these losses to the company, GRIDCo. This is shown in Table 1 and Table 2.

Table 1 : Monthly Energy Transmission Data- 2012

Month	Energy Transmitted (kWh)	Transmission Loss (kWh)	Loss (%)	Allowable Loss (%)	Cost of Losses (GH₵)
January	1,027,235,309.96	60,235,020.90	5.86	3.50	5,104,908.46
February	964,273,773.12	35,593,423.55	3.69	3.50	3,547,907.34
March	1,084,628,341.92	33,697,399.46	3.11	3.50	2,841,516.41
April	1,044,912,208.55	40,771,394.45	3.90	3.50	3,454,511.46
May	1,055,896,290.36	49,781,371.43	4.71	3.50	4,212,994.65
June	982,770,248.68	41,786,487.67	4.25	3.50	3,558,883.03
July	979,616,708.53	39,857,300.82	4.07	3.50	3,367,742.63
August	952,782,770.27	41,677,134.65	4.37	3.50	3,520,473.07
September	949,448,994.96	35,656,425.48	3.76	3.50	3,012,788.59
October	1,021,034,703.33	36,772,197.15	3.60	3.50	3,107,068.62
November	1,039,154,511.93	46,670,072.10	4.49	3.50	3,943,391.18
December	1,063,811,536.80	52,540,394.05	4.94	3.50	4,427,402.99
Total	**12,165,565,398.41**	**515,038,621.71**	**4.23**		**44,099,588.43**

Table 2 : Monthly Energy Transmission Data - 2013

Month	Energy Transmitted (kWh)	Transmission Loss (kWh)	Loss (%)	Allowable Loss (%)	Cost of Losses (GH₵)
January	1,027,235,309.96	60,235,020.90	5.86	3.50	5,104,908.46
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Total	**12,165,565,398.41**	**515,038,621.71**	**4.23**		**44,099,588.43**

From the data above, it can be seen that, 515,038,621.71 kWh and 580,278,509.55 kWh of energy losses were recorded for 2012 and 2013 respectively. These losses, representing 4.23 % and 4.49 % for the respective years, are above the minimum allowable percentage loss of 3.5 %, with the cost of these losses being valued at GH¢ 44,099,588.43 ($12,599,882.41) for 2012 and GH¢ 49,017,455.75 ($14,004,987.36) for 2013. These losses tend to have drastic impact on the operations of GRIDCo. These transmission losses, valued at millions of Cedis, are paid monthly by GRIDCo to the generating companies as penalty for losses above the minimum allowable loss. This is shown in Figure 2.

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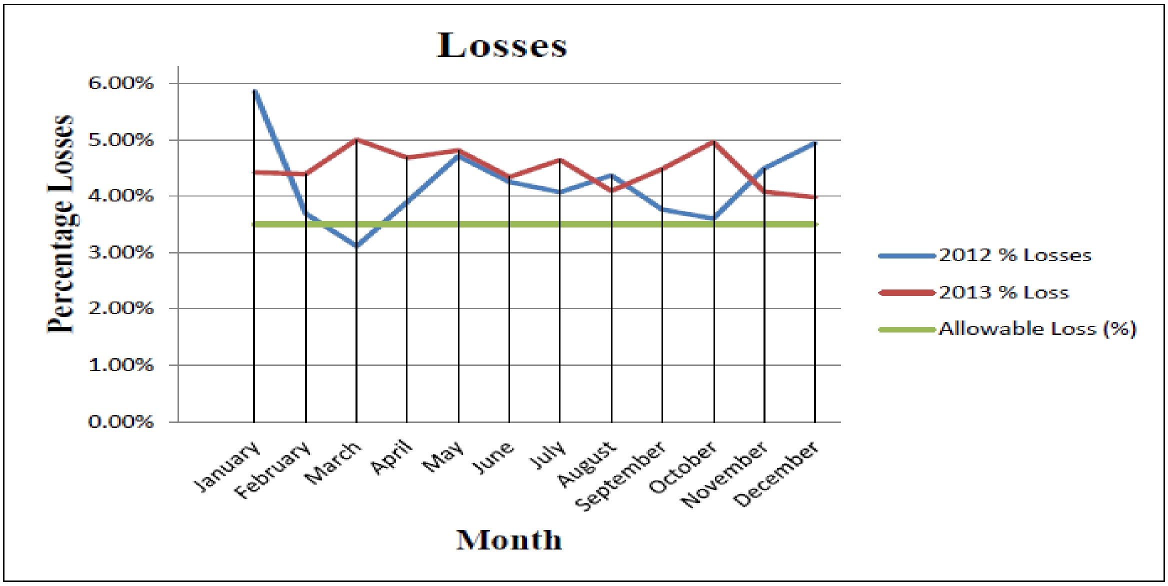

Figure 2 : Losses Recorded for 2012 and 2013

From Figure 2, it is also seen that, the month of January, 2012 recorded the highest percentage of losses, followed by the month of March in 2013. The months of December and October also recorded quite significant losses in 2012 and 2013 respectively. These high losses for the months mentioned earlier, can be attributed to the festive periods, which usually fall on these months. The Christmas and New Year seasons, fall on the months of December and January respectively, whiles the Easter festivities are celebrated in the months of March/April. During these festive periods, the demand for electrical power is very high, due to nation-wide celebrations and activities which all require electrical power, hence, the losses in the system also increases accordingly.

Despite GRIDCo's transmission system being one of the best in Africa, the annual losses on the system seem to have gradually increased, from 4.23 % in 2012 to 4.49 % in 2013, as seen in Table 1 and Table 2. This shows a 0.26 percentage point increase of the losses in 2013 compared to that of 2012. These increasing losses present worrying concerns to GRIDCo as the transmitting utility and to the country as a whole.

It was discovered from interactions with GridCo Engineers that the losses being experienced on the network, resulted from many causes such as generation mix, generation units being positioned far from the load centres, inadequate generating units, the increasing and changing loads in the country, improper metering positioning on the transmission system and inefficiencies on the part of the utility companies (Volta River Authority and GRIDCo).

IV. Analysis and Strategies to Mitigate Technical Losses in the Transmission Network

GridCo's records show one of the key setbacks in the transmission of power to be the issue of voltage instability in some parts of the country. The Power System Simulation for Engineering (PSS/E) software tool, was used to model and run simulations on the entire grid to determine areas on the network violating system pre-set conditions, which contribute to the technical losses on the GRIDCo network and QV curve analysis was used to depict the behaviour of the grid network supply to variations in reactive power and their effects on the voltages in a grid network. Optimum capacitor allocation techniques was adopted, as means of effectively reducing the system instability and ultimately, reduce the losses being experienced.

V. Technical Adequacy Criteria

A number of conditions were used as the basis for the analysis. These conditions include; voltages at all buses should be within the range of 0.95 per unit (p.u) to 1.05 per unit (p.u.) which is the standard set by GRIDCo. Generating plants are to be operated so as not to generate reactive power beyond their designed limits, Power flow on all power transformers and transmission lines should not exceed 85 % of their thermal ratings and transfer limits, respectively.

VI. Results and Discussion

The PSS/E software was used to model and simulate the entire grid to determine areas or bus bars experiencing losses based on the network parameters such as loadings for transmission lines, load centres etc., that was fed into the PSS/E software. It was discovered that a number of areas/buses on the network were violating the system pre-set parameters which is as a result of the radial scheme deployed in such sections, losses arising from the connections and equipment in the network due to extreme environmental conditions. The PSS/E simulation carried out was the best choice as it enabled power flow studies to be done which is very important to determine effective design of power systems, extensive planning and future expansion of existing as well as non-existing power systems. This enhanced the determination of per unit voltages on every bus bar incorporated into the national grid. The areas/ buses in question recorded very low voltages which violated the system pre-set range of 0.95 p.u to 1.05 p.u., as shown in Figure 3. This means the ratio of the transmitted voltage to the reference voltage set at the substation is below the acceptable range to enable effective power to be transported to the bulk distribution companies.

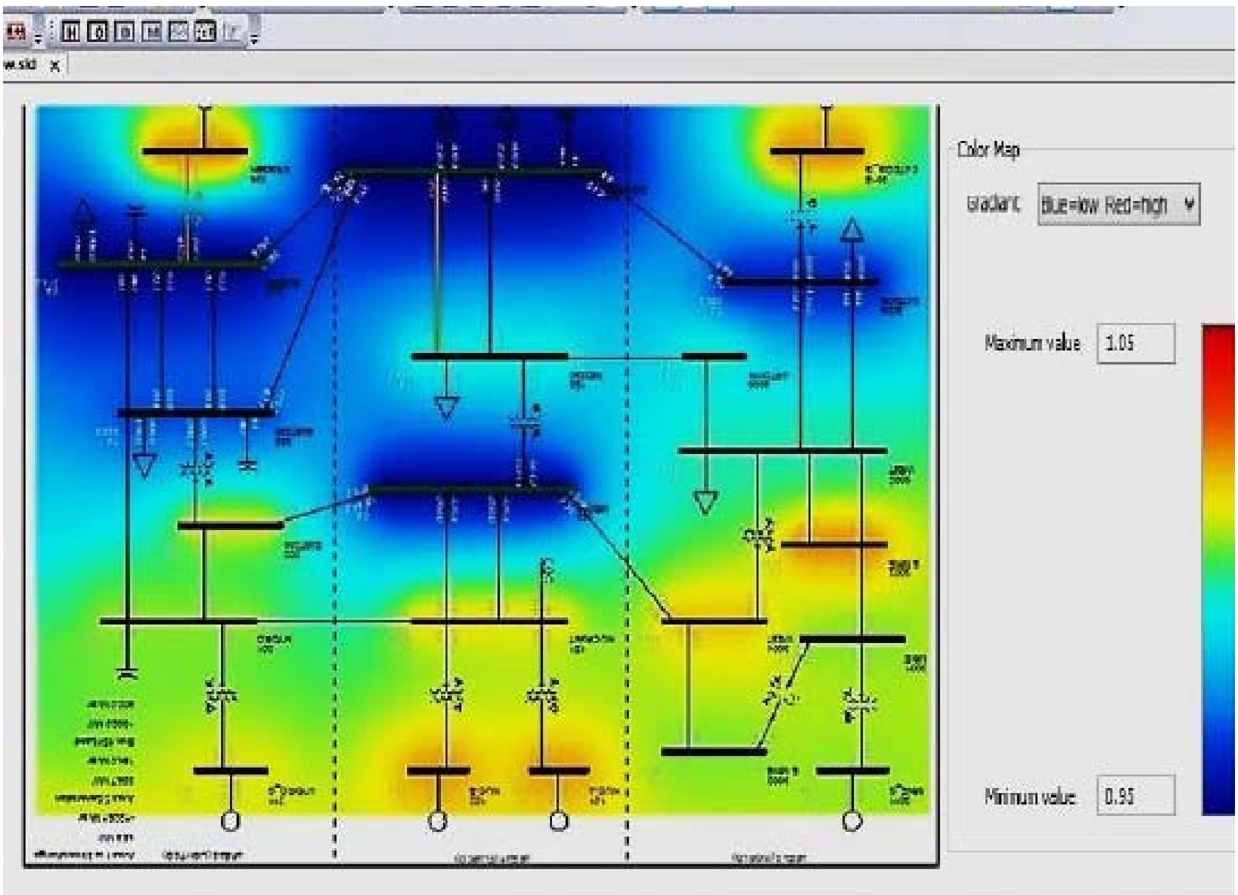

Figure 3 : Results of Simulation of Ghana's National Grid

The design of the national grid is an interconnected transmission system comprising a new 330 kV grid under construction to replace the current 161 kV grid running across the country as the primary transmission voltage, a ringed 161kV transmission lines in the southern sector of Ghana, a single circuit 225 kV transmission line linking Ghana's national grid from a substation in Prestea in the western part of Ghana to Abobo substation in La Cote d'Ivoire, a single radial 161kV transmission lines from Kumasi to the northern regions and a double circuit 161kV transmission lines connecting the Akosombo generating plant in Ghana to Lome substation in Togo, to supply power to both Togo and Benin[10]. Ghana also supplies electric power to Burkina Faso in the north through a low-voltage distribution network that serves the border towns of Po and Leo in Burkina Faso. Also, a planned 225 kV high voltage transmission line is expected to interconnect Ouagadougou, the capital of Burkina Faso to Ghana's grid network as part of the West Africa Power Pool (WAPP) agreement[11]. There are various step down transformers 161/ 69 kV, 161/34.5 kV and 161/11.5 kV at the 53 substations across the country [10]. The standard set by GridCo is to either attain not less than 95 % of the intended voltage transformation or not more than 105% of the intended voltage transformation. The capacity injected into the grid was 1872 MW and 1943 MW for 2012 and 2013 respectively [12]. As seen in Figure 3, the colder (blue) portions of the contour show the areas experiencing under-voltages and the yellow and green sections indicate areas where system parameters are normal. A radial scheme and a ring main scheme are deployed in the northern and southern sections of the national grid network respectively. The simulation revealed majority of the areas/buses in the northern network section displaying colder blue which was in violation of the networks pre-set conditions. The southern network section on the other hand, displayed contour colour yellow and green which was within the normal range of the pre-set conditions of voltage range.

From the reviewed literature, low voltages on system buses were determined to be one of the major contributing factors to causes of technical losses on the transmission system. From Figure 3, most of the areas experiencing these low voltages were found to be in the northern part of the country. As stated earlier, these losses in these areas are as a result of the radial scheme grid network deployed which contributes to voltage drops. The southern part, on the other hand has a ring within rings main scheme grid network system which in itself mitigates voltage drops in the system. The low voltage areas are listed in Table 3.

Table 3 : Areas Violating System Pre-set Conditions of 0.95 – 1.05p.u.Voltage Range

Area	Voltage Recording (p.u.)
Kintampo	0.92
Buipe	0.89
Bolgatanga	0.86
Kumasi	0.88
Konongo	0.92
Nkawkaw	0.94
Techiman	0.89
Tamale	0.88

Further investigations revealed that, these low voltages being experienced in the northern part of the country are as a result of the following: Power travelling long distances from the generating stations (mostly in the south) to these load centers in the north, the increasing and changing loads of these areas, especially Tamale and Kumasi, the radial network systems deployed in some of these areas. Radial network system is a network where still bus feeders are deployed and consumers tap from the still bus feeder closer to the substation to the furthest from the substation. The consequence is drop in voltages for consumers tapping furthest from the substation because the resistance to the flow of current increases with the length of the conductor. So such a connection only results in more losses in the network.

Based on these findings, capacitor banks were installed on critical buses or substations at these areas, including Kintampo, Tamale, Techiman and Kumasi, to compensate for the low voltages being experienced. These selected areas were considered as critical because they are the major load centers in the northern part of the country. The capacitor banks were installed in the GRIDCo substations at these critical areas because, the best type of compensation is compensation implemented at the load centers.

VII. Qv Curve Simulations

QV curve simulation was used to calculate the initial reactive power compensation needed for each critical bus or substation based on the voltage value at that bus, taking into consideration, other close electrical load centers and their distances from the substation or bus being simulated. The QV curves simulated for the critical buses or areas considered are shown below.

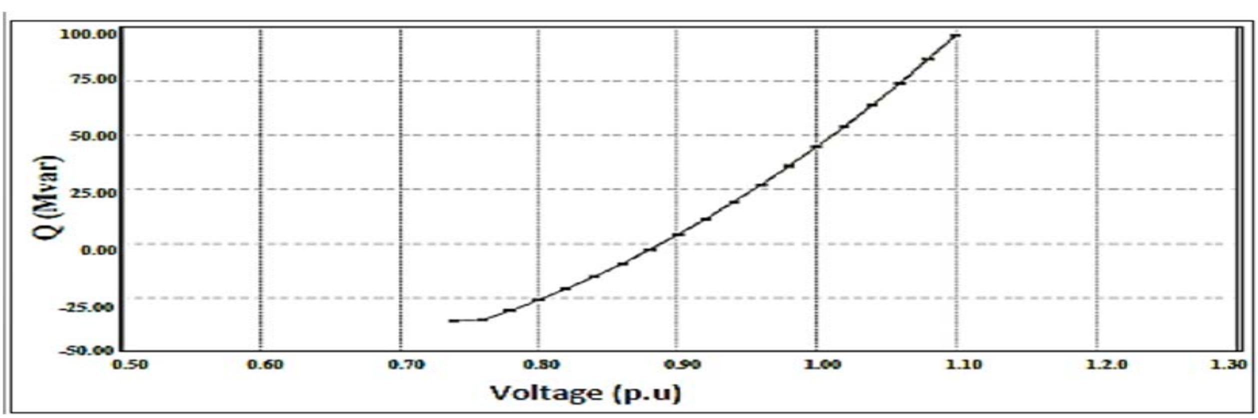

Figure 4 : QV Curve for Tamale

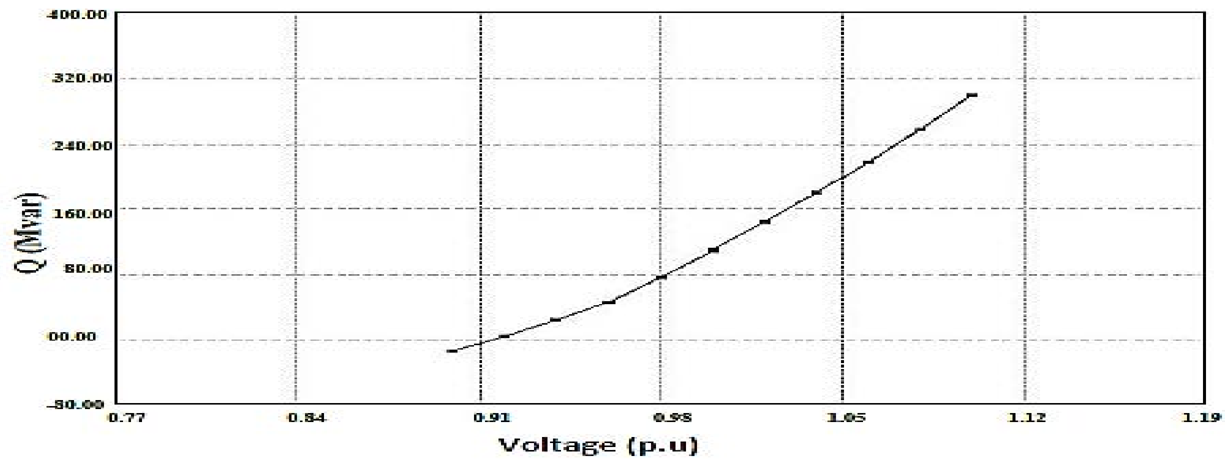

Figure 5 : QV Curve for Kumasi

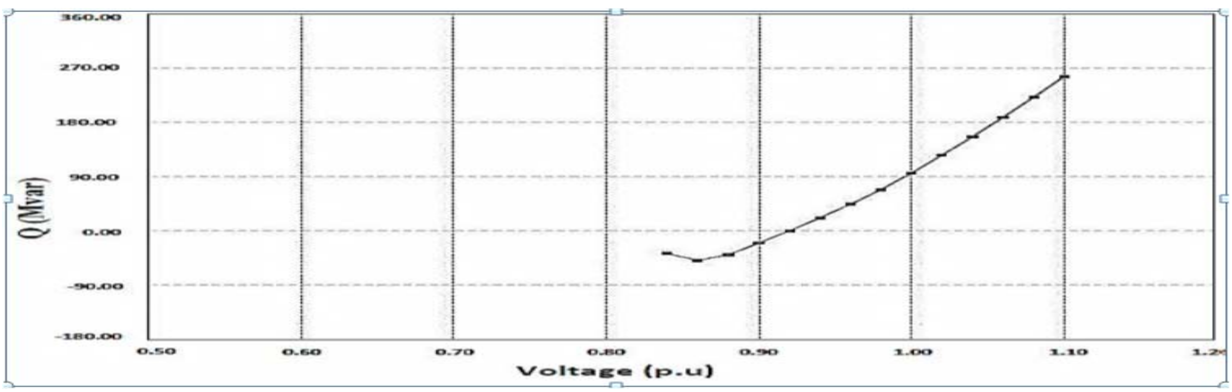

Figure 6 : QV Curve for Kintampo

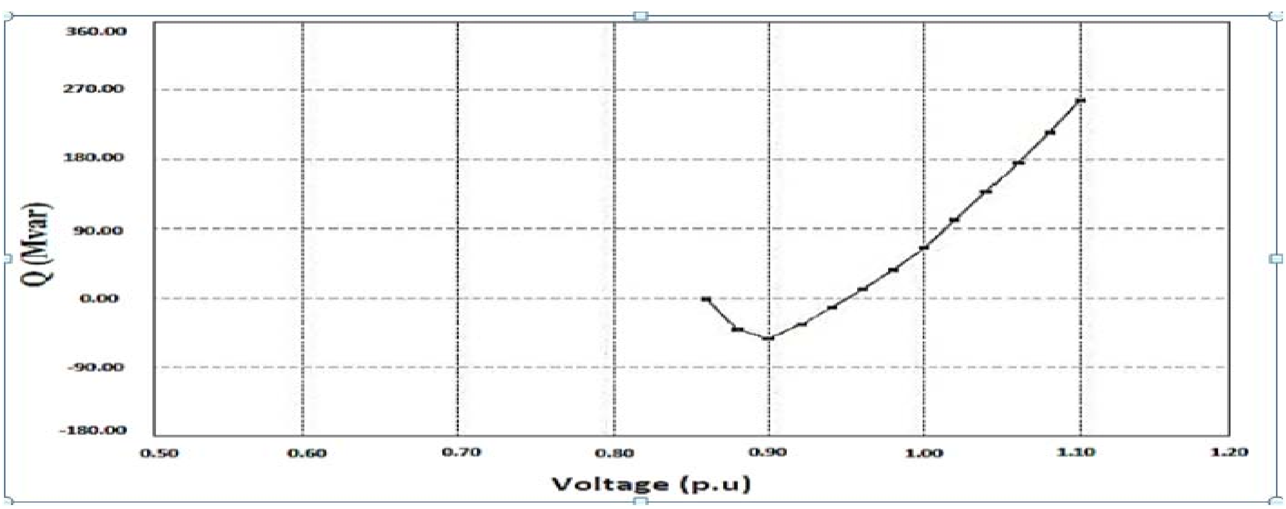

Figure 7 : QV Curve for Techiman

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Based on the QV simulation results, 44.7 Mvar of compensation will have to be installed in the tamale substation, 109.5 Mvar on the Kumasi substation, 65.6 Mvar on the Techiman substation and 92.1 Mvaron the Kintampo substation. These are the amounts of var needed to maintain the voltages of these critical buses at 1.00 p.u and reduce the system losses. These results are tabulated in Table 4.

Table 4 : Compensations Needed Based on QV Analysis

Critical Bus or Substation	Vars Needed (MVar)
Tamale	44.7
Kumasi	109.5
Techiman	65.6
Kintampo	92.1

VIII. Optimal Capacitor Allocation Implementation

On the basis of the QV curves simulation results, optimal allocation of capacitor banks was implemented for all the buses considered as a means of determining in real time, the optimum economic value of compensation in Mvar that is to be placed at each substation taking all the critical buses into consideration in order to reduce the system losses. The analytical method of capacitor allocation was implemented by manually placing capacitor banks on the critical buses simultaneously and simulated using the PSS/E to obtain the optimal compensation to be installed on all the critical buses or substations. Fig. 8 and Fig. 9 show the installed capacitor banks on the critical buses or substations.

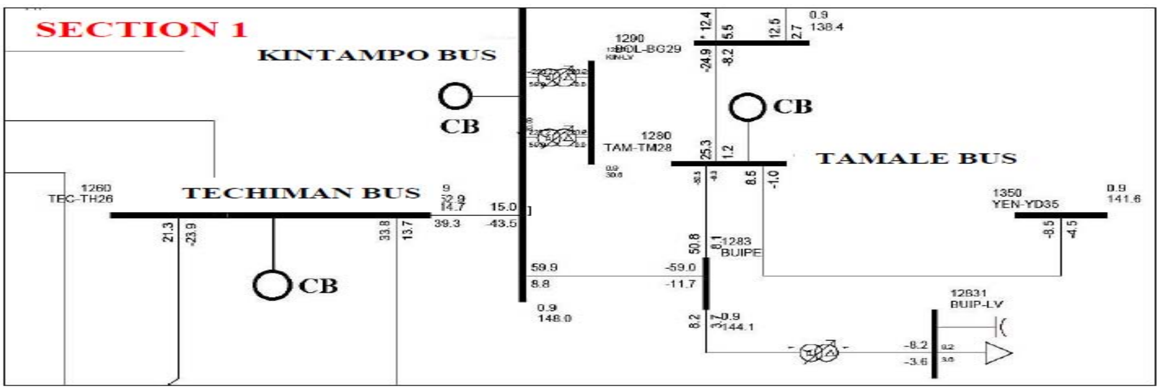

Figure 8 : Capacitor Banks (CB) Installed on Critical Buses in Section 1

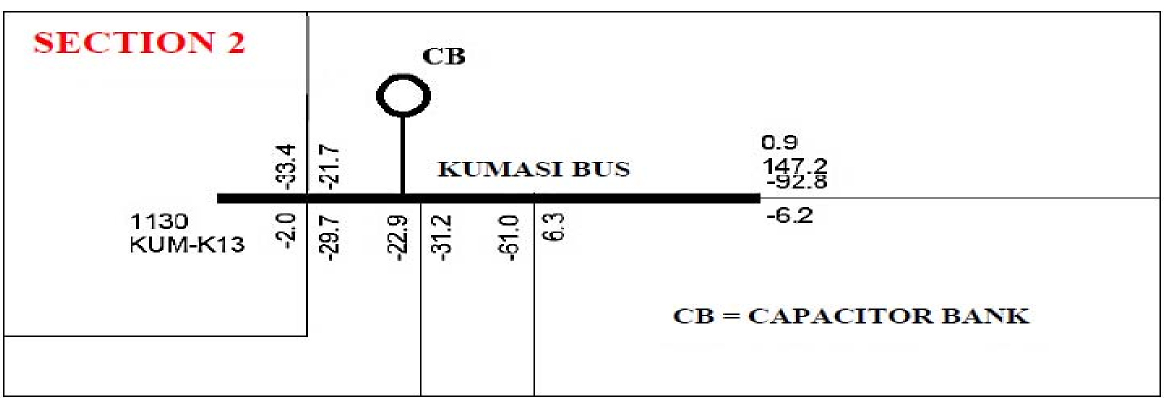

Figure 9 : Capacitor Bank Installed on Kumasi Bus in Section 2

The implementation of optimal capacitor allocation yielded reduced compensations for the critical buses compared to that obtained from the QV curve calculation as seen in Table 5.

Table 5 : Compensations Needed after Optimal Capacitor Allocation

Critical Bus	New Vars (MVar)
Tamale	14.7
Kumasi	84.1
Techiman	-15.4
Kintampo	54.8

From the results of the optimal capacitor allocation simulation in Table 5, lower compensation values were obtained for each critical bus except for the bus at Techiman, which recorded a negative value, indicating that, that bus ends up absorbing the reactive power injected on it. Consequently, this indicates that, no compensation should be provided for the bus at

Techiman since it will lead to over-compensation. Rather, because of the close electrical distance between Techiman and the other critical buses, Techiman will be compensated for by the other remaining buses. Fig. 10 shows the reactive power (var) calculated from the two simulations.

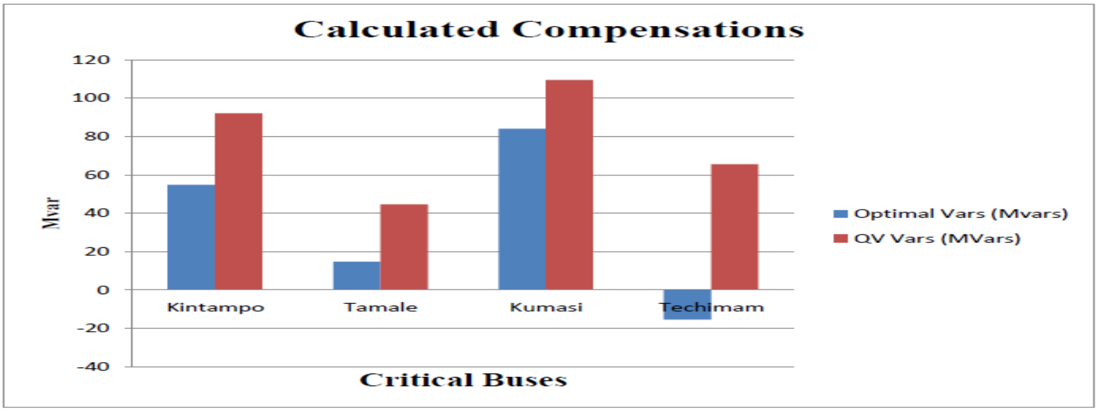

Figure 10 : Calculated Compensations

a) Bus Voltages

The low voltages that accounted for the losses on the system which were recorded at the critical buses or substations during the PSS/E simulations, improved appreciably after the installation of the capacitor banks. These capacitor banks provided reactive power to these buses, based on the optimal capacitor allocation calculations (ignoring the Techiman installation). After the installation of the capacitor banks, the voltages recorded for the critical buses, Kumasi, Kintampo, Tamale and Techiman were 1.00 p.u, 1.00 p.u, 1.00 p.u and 1.02 p.u respectively, compared to the voltage levels when the capacitor banks were not installed. Fig. 11 shows the voltages that were recorded, both before and after the needed compensation was provided at these buses or substations.

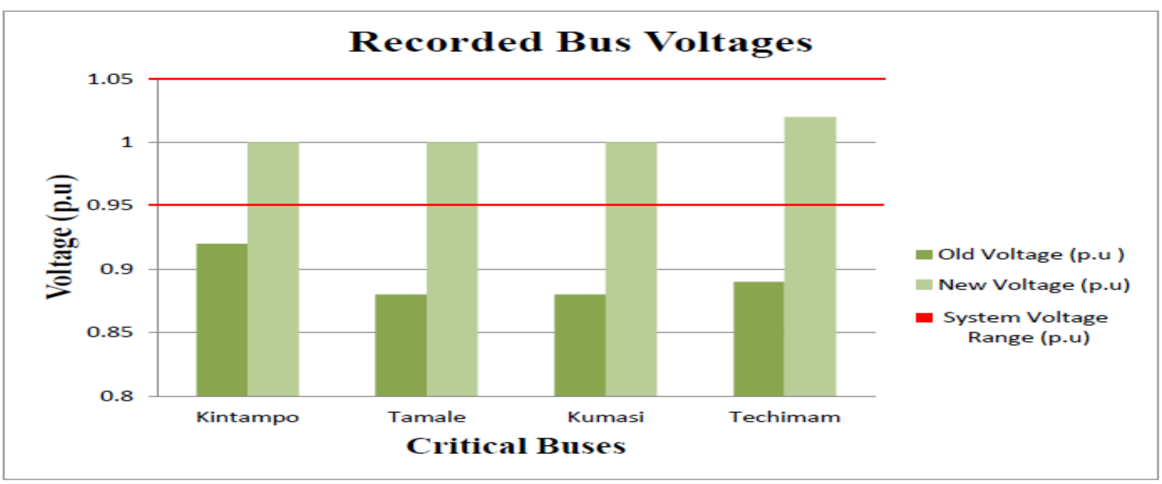

Figure 11 : Voltage Recorded before and after Compensation

b) Losses Recorded

The losses that were recorded on the system at the time of the simulation, that is, before the installation of capacitor banks on the critical buses considered, was 71.7 MW, representing a percentage of 4.07 % of the total system power demand of 1762 MW [1]. These recorded losses on the system reduced immensely after the installation of capacitor banks (neglecting the Techiman installation), which injected reactive power on the selected critical buses to improve the bus voltage. The losses recorded, reduced from 71.7 MW to 65.2 MW. This reduction in losses after the capacitor banks were installed represents a percentage of 3.7 %.

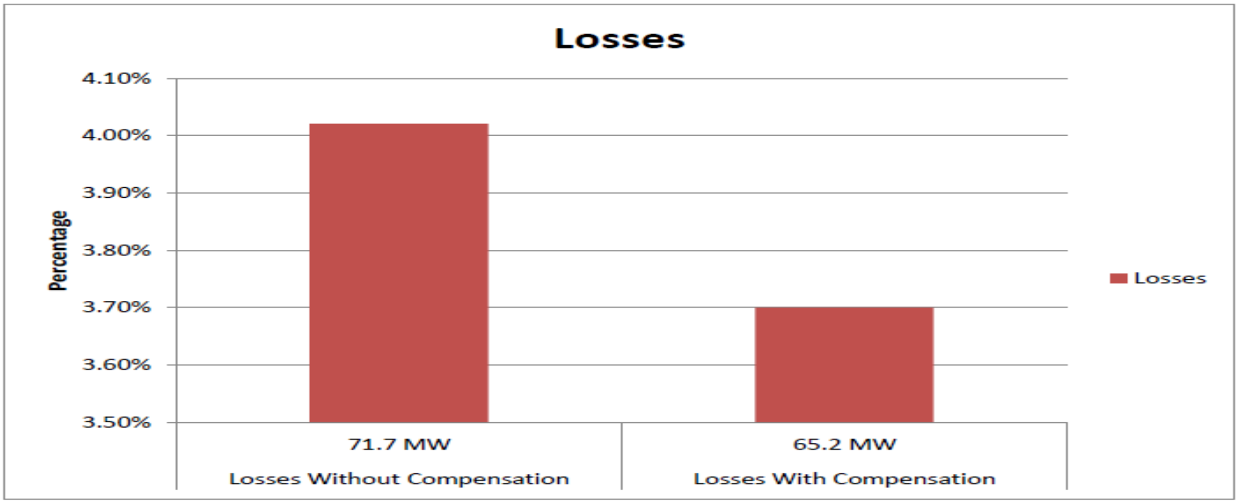

Figure 12 : Losses Recorded

IX. Conclusions

Low voltages in the northern part of the country are a major factor to the losses being experienced on Ghana's transmission network. The PSS/E software, QV curve analysis and optimal capacitor compensation were successfully used to optimally calculate the needed reactive power in the critical buses considered to reduce the losses on the network. A significant quantity of losses was reduced after installation of capacitor banks on the grid network at the bus bars contributing losses. The use of distributed generation (DG) and Smart grid technologies should be adopted to improve the grid system voltage profile in the future. The radial network scheme in the northern sector can also be replaced with ring within rings to help mitigate losses on the grid network.

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