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DOCTORAL THESIS STATEMENT

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Faculty of Electrical Engineering and Information Technology
Department of Electrical Power Engineering

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DEVELOPMENT AND STATIC VOLTAGE STABILITY ENCHACEMENT OF GHANAIAN POWER NETWORK USING FACTS (2010 – 2020)

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1. Pertaining situation of the Ghana power system

Power transmission networks were originally constructed to link generators to load centres which were not too far away. Increase in demand of electrical energy and the spread of industrialization had resulted in the situation where generating plants are located at remote areas from the load centres for economical, environmental and safety reasons. Hence long high or extra high voltage transmission lines are to be used to transmit power from the generating plants to the load centres. With the world being a global village, isolated systems of districts, regional and countries are interconnected for economical reasons. Though these interconnections render benefits like; exploiting load diversity, generation capacity and reserves sharing, and economy of large scale, there is also the possibility of sacrificing security since a disturbance in one subsystem can cascade into other systems resulting in major outages. [1]

It has therefore become necessary for the traditional utility companies to upgrade the transmission system and also expands them by constructing new line thereby creating a more complex mesh but highly reliable network. To ensure reliability, transmission lines are to be operated at far lower than their ratings in other to have reserve margins ensuring that the system can recover from contingencies like heavy loaded line tripping or introduction and generator outages.

On the demand side the customer looks for cheaper, highly reliable and better quality power supply beyond their local power providers. Generation has also become more competitive as Independent power producers and other non-utility establishments are allowed to enter the generation business. This had modified the generation – demand location pattern in the network's configuration and creates new transmission corridors.

Congestion issues are thus becoming increasingly important as some lines are overloaded and others far below their power carrying capacities a reflection of the inadequate control of the utility companies to influence the path of power flow.

Ghana as a growing economy is seeing fast increase in size of her power system and also demand. The situation is aggravated with the additional demand on the system as a result of the West African Power Pool projects which seeks to interconnect member states into a common power pool. Ghana seems to be the one of the possible backbones to the success of this project since she is to support neighbouring countries of Togo, Benin and Burkina Faso. Therefore for the WAPP project to succeed, Ghana ought to have a reliable, static and dynamic stability as well as supporting the energy balance equation of the sub region.

Historically, the Ghana power network was build along the coastal belt to provide power to the two hourbour towns of Takoradi and Tema. For this reason the industrial base of the country was concentrated at the same coastal belt so it is for power generating plants. With the expansion of the transmission network to cover the entire country and the spread of power demand in some far away distances demands that huge amount of power is transmitted from generation sites to the load centres. In some cases very low power is transmitted over a long distance in other to serve the social responsibility of the State. In addition to the state's social responsibility, mining, other extracting and agro-processing industries are springing up in remote areas which necessitate the extension of power to those areas. The above mentioned reasons coupled with the periodic shortage of energy supply had seen the country going into partial or total blackouts in recent times. The situation gets worst with the lost of a weak inter-tie between Ghana and her neighbours.

Taking into considering the above mentioned issues, the main task of this thesis is to make a proposal to systematically develop the network based on the committed and known planned investment of the government of Ghana as well as partners in the power generation-transmission-distribution industry over the period 2010 - 2020.

A preliminary analysis of the 2010 base peak load scenario revealed that the system was not voltage stable as a result of deficit in reactive power and its ill distributed nature.

With the fast changing of the nature and demand on power systems, traditional ways of solving transmission and developmental problems are no more appropriate therefore, the use of the state of the art technology has to be employed. The possibility of using Flexible A. C. Transmission System (FACTS) devices in order to ensure voltage stability of the systems is also investigated. Considering the demand on the system alongside the scope of this thesis, the most cost effective in terms of facility usage was used in the research.

2. Objectives of this Doctoral Thesis

As the title of this thesis suggests, the main objective is of two parts;

- To develop and expand the Ghana power system to meet the power demand in terms of location, magnitude and reliability over the period of 2010 to 2020. The reference and limitation to the extent of expansion and development is the knowledge of the committed and planned generation facility and the power demand forecast as well as known possible bulk demand in magnitude and location.
- To assess the limits of static voltage stability of the proposed configurations and improve on them using FACTS technology.

3. Methodology

In any research work the integrity of the obtained results is dependent on models, numerical techniques and control settings used. In chapters 2 & 3 of the main thesis, detail modeling and mathematical descriptions of general system components and FACTS devices had been given. The models used in this thesis are implemented in the Matlab based research and educational software package Power Systems Analysis Toolbox version 2.1.6 (PSAT) written by Associate Professor Federico Milano. The models and numerical techniques implemented in PSAT and used in this work are briefly discussed in chapter 8. Throughout the simulation, a single slack bus concept, constant PQ loads and PV limits were observed. [2,3]

3.1 Numerical Techniques used

Newton-Raphson algorithms for solving the power flow problem are formulated as follows;
The active and reactive powers are expressed as;

$$P_i = \sum_{j=1}^{n}|V_i||V_j|\,|V_{ij}|cos(\theta_{ij} - \delta_i + \delta_j) \qquad 3.1$$

$$Q_i = \sum_{j=1}^{n}|V_i||V_j|\,|V_{ij}|sin(\theta_{ij} - \delta_i + \delta_j) \qquad 3.2$$

And the problem to solve is expressed in matrix notation as;

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \qquad 3.3$$

Where, the Jacobian matrix is the linearized relation between small changes in angle and voltages with changes in the real and active powers.
After each iteration corrections are made to the scheduled variables through equations 3.4-3.7 and the next solution found.

$$\Delta P_i^k = P_i^{sch} - P_i^k \qquad 3.4$$

$$\Delta P_i^k = Q_i^{sch} - Q_i^k \qquad 3.5$$

$$\delta_i^{(k+1)} = \delta_i^k + \Delta\delta_i^k \qquad 3.6$$

$$|V_i^{(k+1)}| = |V_i^k| + \Delta|V_i^k| \qquad 3.7$$

If the predetermined degree of accuracy expressed in eq 3.8 is not achieved the process is repeated until the residuals are less than the accuracy

$$|\Delta P_i^k| \le \varepsilon \; and \; |\Delta Q_i^k| \le \varepsilon \qquad 3.8$$

3.2 QV – Sensitivity Analysis

PSAT implements three forms of QV sensitivity analysis base on the Jacobian matrix used.
The Jacobian matrices are;

1. Standard power flow Jacobian matrix (J_{LF}) , which is obtained from the static equations of power flows in transmission lines and transformers.
2. Complete Jacobian matrix of the power flow equations of the system (J_{LFV}).
3. Dynamic power flow Jacobian matrix (J_{LFD}), which is computed from the complete matrix.[2]

Based on the nature and scope of the work done under this thesis, the standard power flow Jacobian matrix was used. The input matrix is the load flow Jacobian matrix of eq. 3.9

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\theta} & J_{PV}\\ J_{Q\theta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \qquad 3.9$$

A reduced matrix defined by the expression;

$$J_{LFR} = J_{QV} - J_{Q\theta}J_{PQ}^{-1}J_{PV} \qquad 3.10$$

Putting $\Delta P=0$ and sub-matrix J_{PQ} not singular, the sensitivity expression is given in the form;

$$\Delta Q = J_{LFR}\Delta V \qquad [2\text{-}4] \qquad 3.11$$

3.3 Continuation Power Flow and N-1 Analysis

The continuation power flow method based on the predictor-corrector step technique with the possibility of using a local parameterization or a perpendicular intersection is implemented in PSAT. The formulation of the problem originates from the standard power system model on non-linear differential and algebraic equations with zero first time derivatives [2,6] which is gives the expressions;

$$0 = f(x, y, \lambda) \tag{3.12}$$

$$0 = g(x, y, \lambda) \tag{3.13}$$

where, x and y are the state and algebraic variables and λ the loading factor. The reactive and active powers are therefore expressed as;

$$P_G = (\lambda + \gamma k_G)P_{GO} \tag{3.14}$$

$$[P_L\,, Q_L] = \lambda[P_{LO}, Q_{LO}] \tag{3.15}$$

P_{GO}, P_{LO}, Q_{LO} are the base case powers of the generators and load respectively, k_G and γ are the scalar variables and participation factor of losses among generators. P_G, P_L *and* Q_L are the maximum powers of the generators and load respectively.

To ensure practicable results of the CPF simulation, limits of generator reactive power, voltage and line flow were implemented. In addition to that the following settings were made:

Voltage tolerance – 0.005.

Line flow tolerance – 0.01.

Step size control set between 0.05 and 0.5 for different cases.

Stop criterion – complete nose curve.

3.4 Time Domain Simulation

In PSAT, two methods of time domain simulation are implemented thus, trapezoidal rule and forward Euler which are A-stable algorithms and use a complete Jacobian matrix to evaluate the algebraic and state variable directions at each step. For the purpose of this work the trapezoidal method is employed. The formulation of the problem is expressed as;

$$0 = f_n\big(x(t + \Delta t), y(t + \Delta t), f(t)\big) \tag{3.16}$$

$$0 = g\big(x(t + \Delta t), y(t + \Delta t)\big) \tag{3.17}$$

where f, g, f_n are the differential, algebraic equations and a function dependant on the integration method respectively. Newton Raphson method is then used to determine the increment in both the state and algebraic variables and subsequent updating of variables through the expressions:

$$\begin{bmatrix} \Delta x^i \\ \Delta y^i \end{bmatrix} = -[A_c^i]^{-1} \begin{bmatrix} f_n^i \\ g^i \end{bmatrix} \tag{3.18}$$

$$\begin{bmatrix} x^{i+1} \\ y^{i+1} \end{bmatrix} = \begin{bmatrix} x^i \\ y^i \end{bmatrix} + \begin{bmatrix} \Delta x^i \\ \Delta y^i \end{bmatrix} \tag{3.19}$$

where the matrices $A_c^i$and function f_n^i are defined at each iteration. When employing trapezoidal method of integration they are expressed as;

$$A_c^i = \begin{bmatrix} I_n - 0.5\Delta t F_x^i & -0.5\Delta t F_y^i \\ G_x^i & J_{LFV}^i \end{bmatrix} \tag{3.20}$$

$$f_n^i = x^i - x(t) - 0.5\Delta t\left(f^i + f(t)\right) \tag{3.21}$$

4. Models of used Components

4.1 FACTS Devices

Different models of FACTS devices are implemented in PSAT namely; SVC, TCSC, STATCOM, SSSC, UPFC and HVDC. Preliminary simulation of the networks under this work revealed unstable voltage conditions due to lack of sufficient reactive power and also the available reactive power is ill distributed which call for reactive power compensation to ensure voltage stability. For this reason the only required FACTS device considered to be enough to solve the voltage problem is the SVC.[2,3] Again considering the scope of work, a model of SVC which assumes a total b_{SVC} expressed by the following differential and algebraic equations was used:

$$\dot{b}_{SVC} = \left(K_r\left(V_{ref} + v_{POD} - V\right) - b_{SVC}\right)/T_r \qquad 3.22$$

$$Q = b_{SVC}V^2 \qquad 3.23$$

The following parameters were therefore used in the simulation for all the SVCs in other to meet the reactive power compensation for the different configurations:

Regulator time constant T_r= 0.001s

Regulator gain K_u = 9.58 pu/pu

Reference voltage V_{ref} = 1pu.

Susceptance range B = (0.6 to -0.6)pu. at 100MVA base.

4.2 Slack generator

The Slack generator is modelled as Vθ bus with the following expression:

$$\theta = \theta_0, and\ V = V_0 \qquad 3.24$$

4.3 PV Generator

Power injected and voltage at generator bus is kept fixed and expressed as:

$$P = P_g, and\ V = V_0 \qquad 3.25$$

4.4 PQ Load

PQ loads are modelled as constant active and reactive powers and in case of voltage violation the powers are expressed as;

$$P = \frac{-PV^2}{V_{Lim}^2}, and\ Q = \frac{-QV^2}{V_{Lim}^2} \qquad 3.26$$

where V_{Lim} in this thesis is equal to V, thus conversion of loads to constant impedances was not allowed.

4.5 Shunt Compensator

Shunt impedance is described by the following equation:

$$P = -gV^2, and\ Q = -bV^2 \qquad 3.27$$

where, g and b are the conductance and susceptance respectively and are included in the network admittance matrix Y. The conversion used is that, negative b represents inductive charge and positive for capacitive. No shunt conductance is implemented in the thesis.

5. Scope of work

The sequence of the total work involved under this thesis is as follows:

- Data correction as stated in chapter 6 of the main thesis.
- Base peak load forecast for various annual configurations. Deviations from the base cases were made to determine the high and low base peak loads.
- Simulation of the 2010 base case to determine the needed measures to be taken.

- Improvement to the past year configuration to meet the demand of the following years networks.
- Numerical analysis of all the various scenarios and necessary improvement strategies made.
- Comparison made between the network with and without the improvement strategies through FACTS technology.
- Recommendations and suggestions for future work and implementation were made.

6. Results

Some selected results of the numerous analysis to determine the state of the network and the required steps to take in other for the systems to meet the basic requirements of a working power system are presented here.

6.1 Base Peak Load Forecast

Different variants of load forecast studies were made available to the researcher. Considering the historical growth from 2000 to 2009 as made available by VRA, a compound annual growth of 4.2% without VALCO and 1.4% including VALCO.

Another historical data provided by VRA and GRIDCo, is the Generation and Consumption statistics for the period 1992-2009, which shows an annual generation increase of 2.43% and domestic load by 2.29%.

A coincidental peak load forecast was first extracted from the various load forecasts made available to the researcher.

Taken into mind the ongoing rural electrification project embarked on by the Government of Ghana which resulted in drastic load growth in the period before 2009, the researcher rested on a simple annual growth rate of 4% for domestic and industrial loads. VALCO and mining loads are kept at constant values since they are well established and had operated stabilized loads in the past.

Having taken into consideration of all the information at hand, the researcher divided the forecast period into two sections namely: 2010 – 2015 and 2015 -2020.

A correlation analysis was made between the coincidental and base peak loads and the results given in table 5.1, and a graphical representation of the results of the correlation analysis together with the high and low peak loads is shown in figure 5.1.

Table 6.1. Results of correlation study

	COINCIDENT PEAK LOAD FORECAST	*BASE LOAD FORECAST*
COINCIDENT PEAK LOAD FORECAST	1	
BASE LOAD FORECAST	0.983088149	1

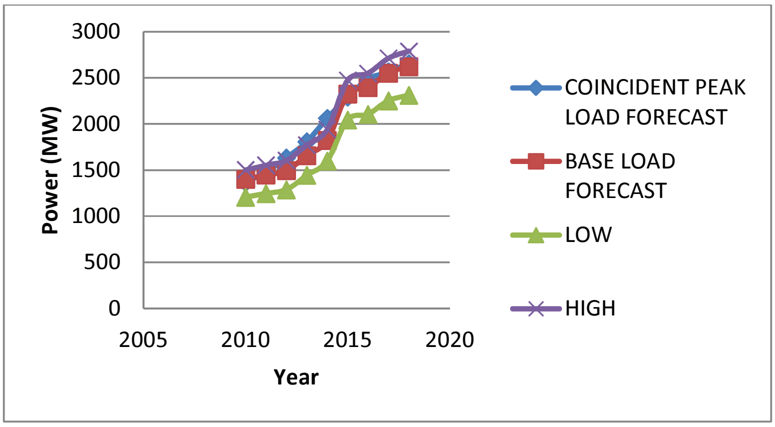


Figure 6.1. Graphical representation of correlation of forecasted scenarios

This gives an indication that the forecasted peak loads under this work have a high probability that they will be very close to the actual peak load in the projected years.

6.2 Power Flow

To determine the load-generation balance, a power flow analyses were carried out for all the various configurations. The results of the 2010 and 2020 year configurations are here presented. Figure 6.2 and 6.3 give the base peak load voltage profiles and figures 6.4 and 6.5, a visual representation of the load profiles.

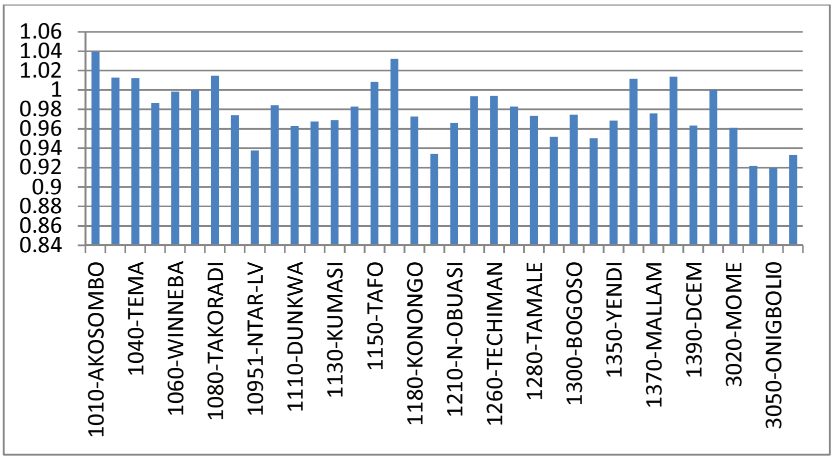


Figure 6.2. Voltage Profile of load buses at 2010 base peak load

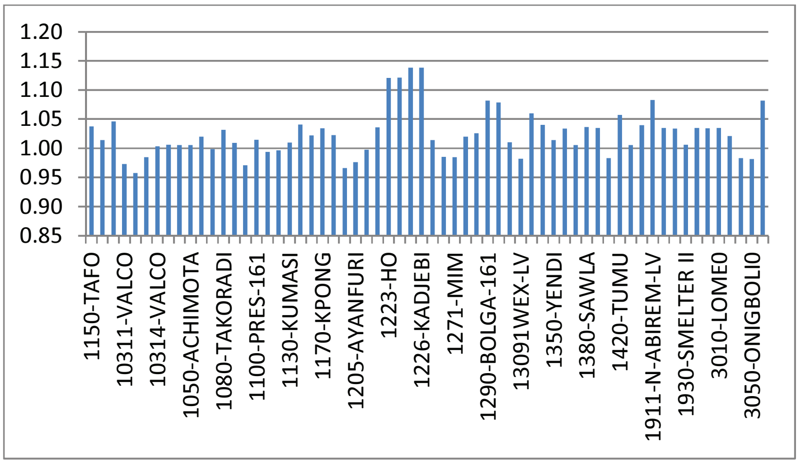


Figure 6.3. Voltage Profile of load buses at 2020 base peak load

The load flow analysis conducted on the selected networks shown that they are adequate for the forecasted base peak load scenarios. However under the 2010 scenario shown a reserve margin less than the capacity of all the generators with the exception of those at SIE generation plant and as such could not support N-1 contingency. Similarly, the final 2020 network also has a reserve of 70.377MW meaning that it could not support N-1 contingency.

In the case of the low peak load scenarios, the systems proved resilient with SVCs compensation range of -50MVar to 40MVar for the two proposed SVCs at Tamale and Kumasi.

The high peak load cases reveal that generation was not enough to support N-1 contingency for the year between 2015 and 2020 since generation reserves were between 90MW and 148MW which is less than the capacity of any of the generators at Akosombo. In the case of 2010, the existing SVC at Kenyasi exceeds its maximum limit of 40MVar by 56.21% and a generation deficit of 121.06MW. The 2020 requires an importation of 125.13MW to meet the load demand.

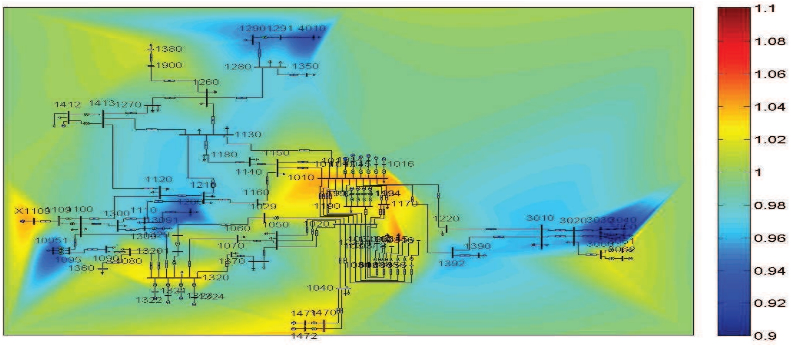


Figure 6.4. Visual representation 2010 base peak load of voltage profile

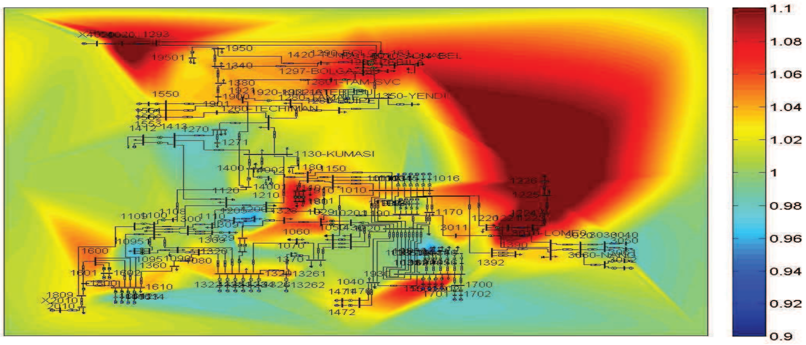
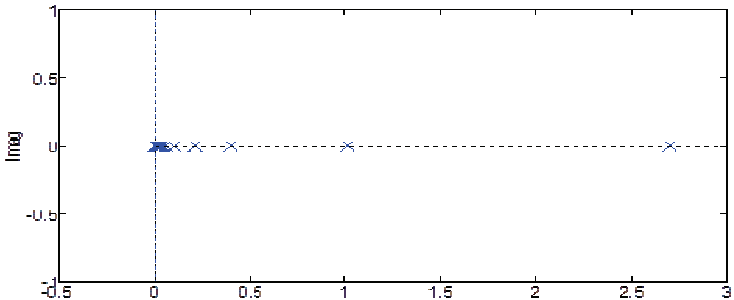


Figure 6.5. Visual representation 2020 base peak load of voltage profile

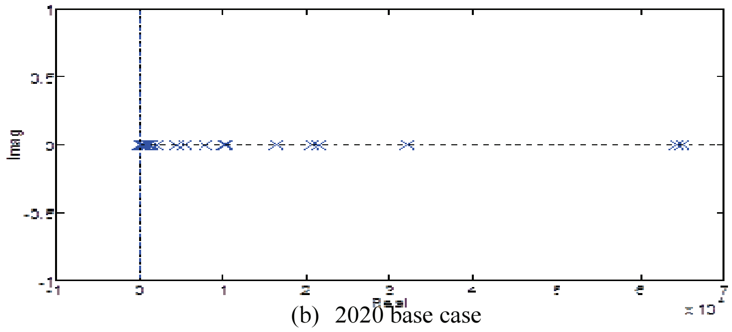
It is therefore recommended that arrangements are made to increase the available generation of 2020 by a minimum of 350MW to ensure reliability of the system at the forecasted high peak load condition under generation contingency situation.

6.3 Power Flow Sensitivity

Eigenvalue sensitivity analysis offers a powerful tool in determining the proximity to voltage instability and also knowledge on the mechanism that leads to that instability of the system.



(a) 2012 base case

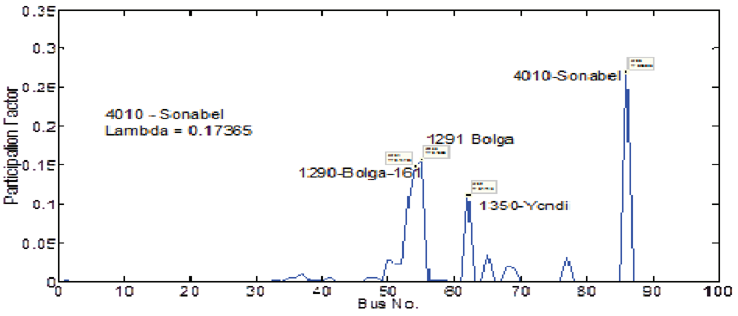


(b) 2020 base case

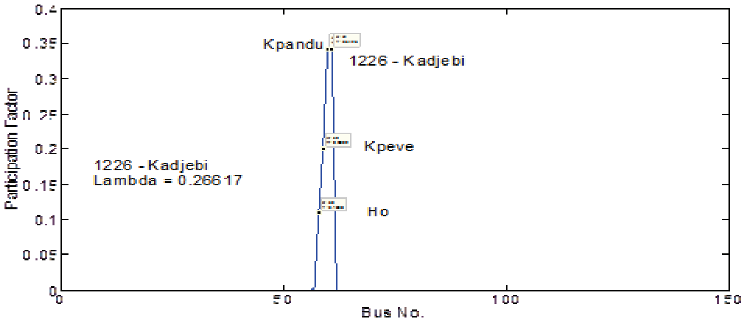
Figure 6.6. Eigenvalue Analysis for base peak load case

The method therefore is used to identify weak load areas or buses which could lead to voltage instability and the responsible load buses or load areas contributing significantly to that condition through the use of participation factor.

Voltage stability of a system depends on how active and reactive power changes affect the voltage of its buses. Under this sensitivity analysis, the relationship between variation in voltages with respect to variations in reactive power injection or absorption is examined. Due to the installed SVCs, the sensitivity analysis was carried on the full power flow Jacobian matrix. The sensitivity analysis was performed on all the selected year based peak load configurations. The simulation results as presented in figures 6.6(a) and (b) for 2012 and 2020 years respectively, indicates that all the configurations are of positive QV sensitivity suggesting that they are all voltage stable under small signal disturbances. Figure 6.7. shows the load buses or load areas participating in rendering the most critical mode of the various configurations.



(a) 2012 base case- bus 4010-Sonabel



(b) 2020 base case - bus 1226 - Kadjebi

Figure 6.7. Participation factor of the most critical mode eigenvalue (λ) for peak load base case configuration.

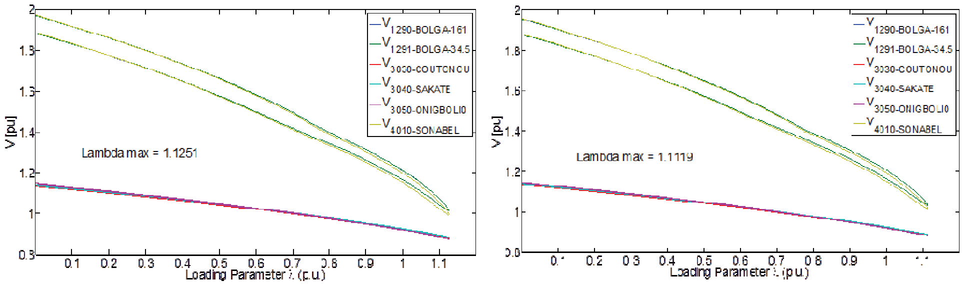
Voltage sensitivity analysis had been carried out on the various systems to ascertain the voltage stability level. From the analysis given above it is clear that the Bolgatanga-Tamale area has the potential of becoming voltage instable. The 69kV line is a source of voltage instability. The participated buses are local, thus the buses affects themselves. It is therefore recommended that the line after it is converted to 161kv line be hocked to the Yendi load bus. This will put it in the ring to ensure voltage stability.

6.4. Continuation Power Flow Analysis and N-1 Contingencies.

Voltage instability leading to voltage collapse has become a concern due to resent partial and total blackouts experienced by the country. This chapter therefore seeks to investigate to what extent do the various system configurations are voltage stable. Among the various methods of static voltage stability analysis, continuation power flow is used to determine the margin to instability. The base peak load configurations of the various years were simulated under normal operating conditions and also under generator and line contingency conditions.

To reduce the volume the number of simulations, only a generator each was taken out of service at the three main generation plants: Akosombo, Aboadze and Bui. Kpong generating plant was left out due to its closeness to the Akosombo plant. Similarly, selected line contingencies were simulated to assess

the ability of the systems to cope with disturbances that do affect the back bone and WAPP interconnection lines.

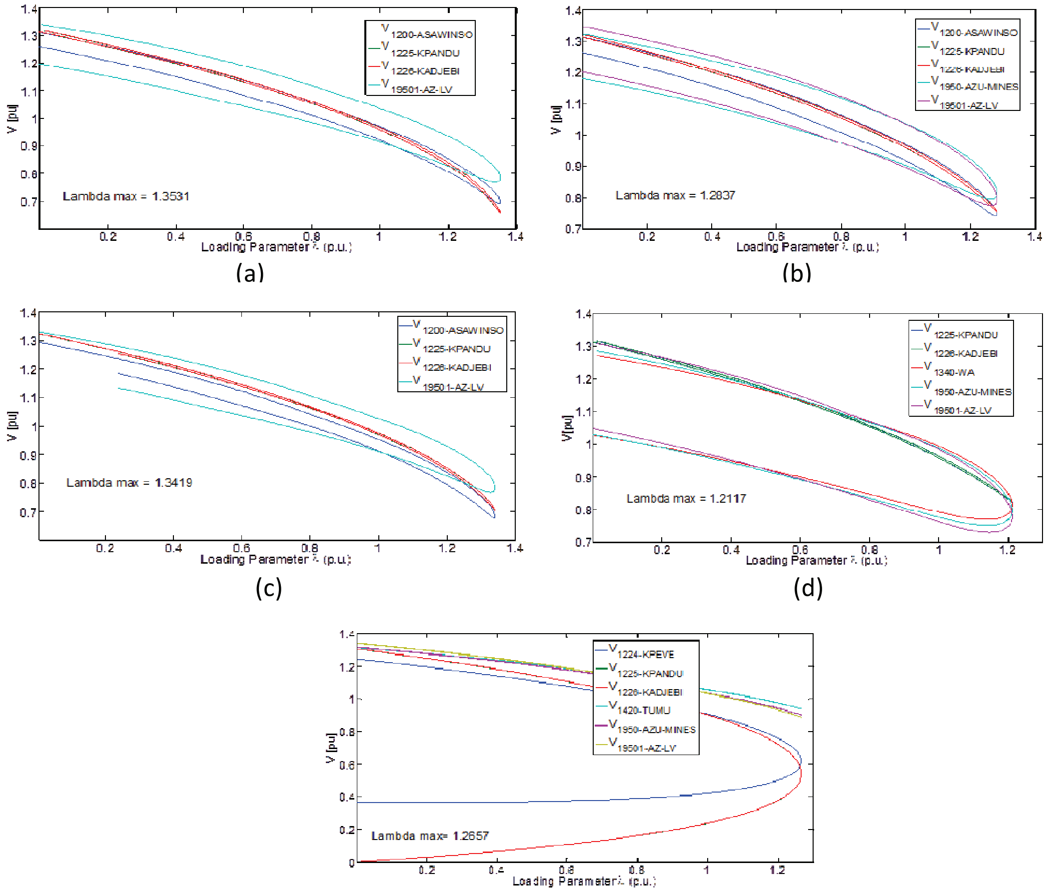


(a) (b)

Figure 6.8. Nose curves for 2012 configuration, (a) Normal operating condition (b)Line 1329-1029, 330kVoutage contingency

Also comparison is made between configurations with all the three SVC installed and with only the existing Kenyasi SVC and the existing SVC with either the Tamale or Kumasi SVC added.

In the case of 2012, the system configuration turned out to have voltage stability under normal operating condition and under only one line contingency condition. All other contingencies were not sustainable. The result is as shown in figure 6.8.



(a) (b) (c) (d) (e)

Figure 5.9. Nose curves for 2020 configuration, (a) Normal operating condition,(b) Normal operating condition without SVC at Tamale and Kumasi, (c) Line 1328-1029 outage contingency, (d) Line 1921-1297 outage contingency, (e) Line 1029-3011 outage contingency

The 2020 base system configuration exhibited lack of adequate capacitive power to sustain voltage during small disturbances. To rectify the situation, a fixed compensation of 0.1pu capacitive reactive power was installed at the Kenyasi SVC bus and that at the Kumasi SVC bus increased from 0.216pu to 0.6pu. The simulation results indicate the worst scenario to have a loadability margin to voltage collapse of 12.17% above the nominal loading level. The overall effect of the two additional SVCs at Tamale and Kumasi raise the loadability margin of the system under normal operating condition from 28.37% to 35.31%. The nose curves are as shown in figure 6.9

Small signal stability analysis had been carried out on all system configurations and scenarios. System reactive power deficiencies had been address throughout the system development. The limits of the installed and proposed SVCs were not able to sustain voltage stability during small signal disturbances of the system through the design period, therefore capacitors of the following power ratings were installed to support the SVCs: 0.1pu at Kenyasi, 0.216pu at Tamale and 0.6pu at Kumasi. In addition, the 69kv live in the Volta region is converted to 161kv and a 161kv line also constructed from Wa to Tumu.

6.5 Time Domain Simulation

In other to study the systems behaviour under large disturbances, generator and line outages were simulated in the time domain routine. Precisely, one generator each from Akosombo, Aboadze and Bui generating plants were taken out of circuit during the simulation and the system voltage response observed. Similarly, thirteen major lines forming the backbone network were taken out of circuit during time domain simulation and system behaviour monitored. The system was perturbed at time t=10sec with a total simulation time of 20sec. This was to text the systems' ability to settle at a new system equilibrium point of operation after a long period disturbance without system failure. The responds of the system at the compensated buses as well as the inter reaction on the SVCs among themselves were particularly observed and presented.

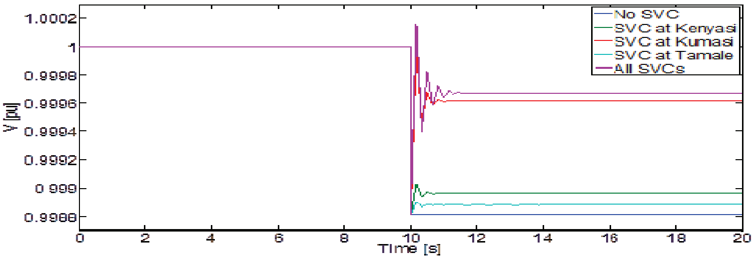
To ascertain the inter reaction between the SVCs, the configuration with SVC was simulated with one SVC at a time and compared the results obtained to that of the no SVC and all SVCs configurations. The results of various contingencies of the mid-period (2015) configuration are discussed below.

6.5.1 Generator trip

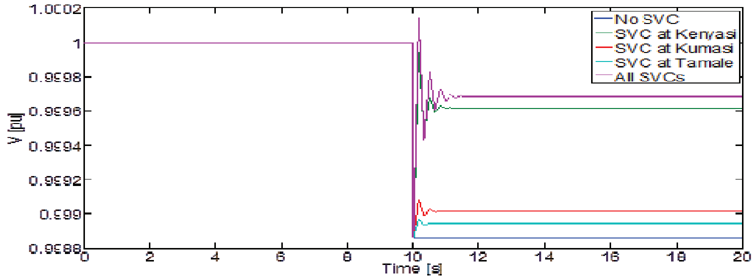
In the cases of generator trip at both Akosombo and Aboadze, the simulation results revealed that all the SVCs complement each other in controlling Voltages at their buses.

On the other hand a generator trip at Bui generating plant showed either no interaction or a negative interaction among the SVCs. The SVC at Kenyasi does not play and role in controlling voltages at the Tamale and Kumasi compensated buses whiles, the Tamale SVC a negative interaction resulting in under compensation and the Kumasi SVC causes over compensation at the Kenyasi bus. .

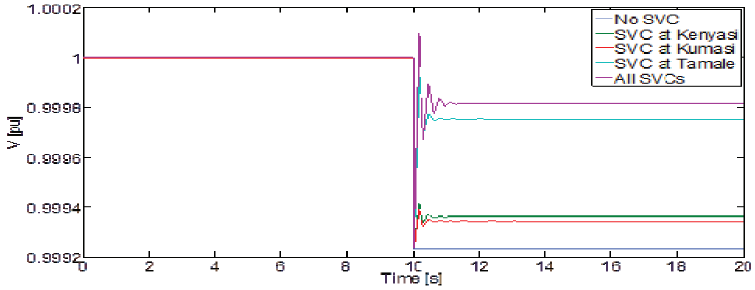
Graphical presentation of the voltage response at the compensation buses of the time domain simulations are as shown in figures 6.10 to 6.12



(a)

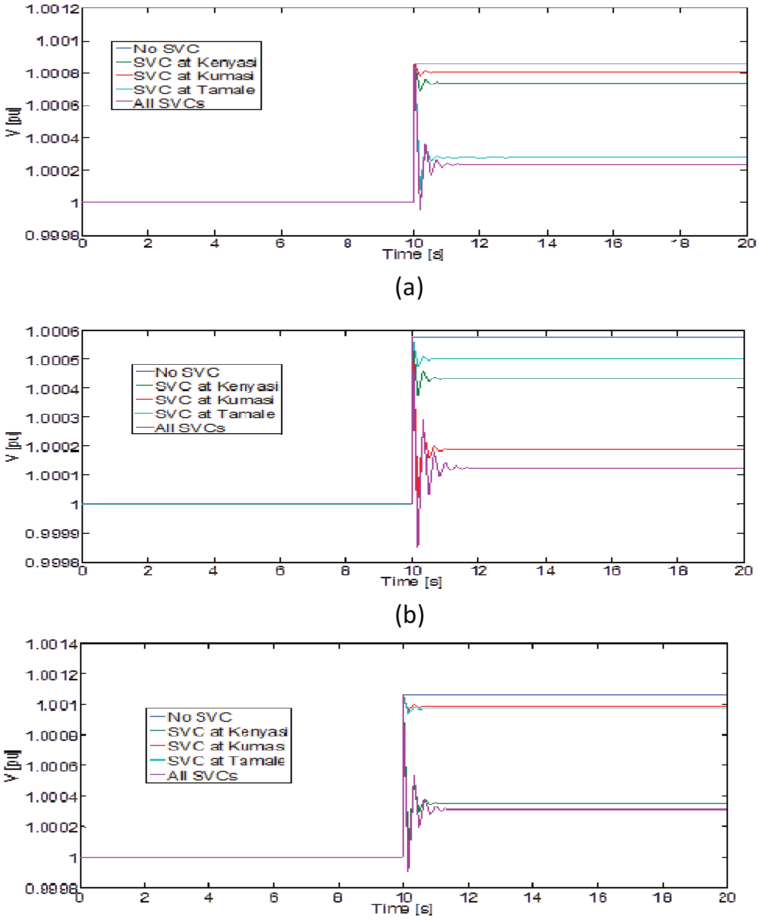


(b)



(c)

Fig.6.10 Voltage profile for time domain simulation with one Akosombo generator outage. (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

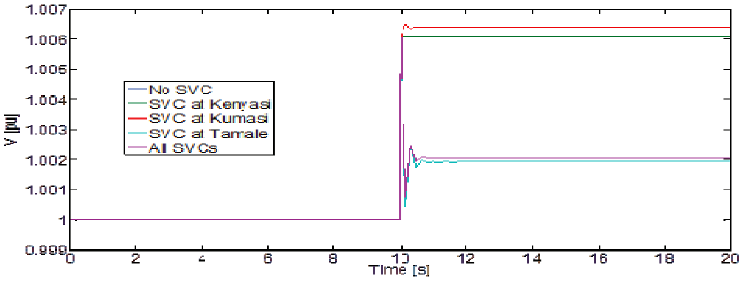


(a)

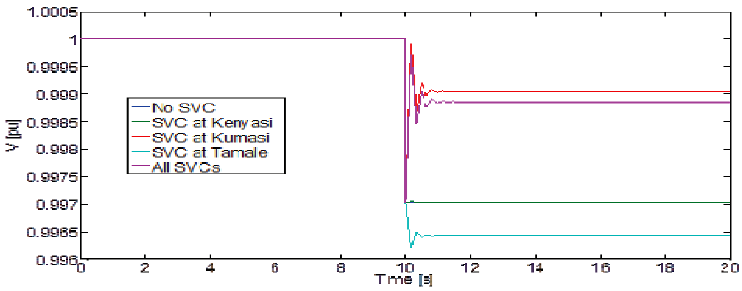
(b)

(c)

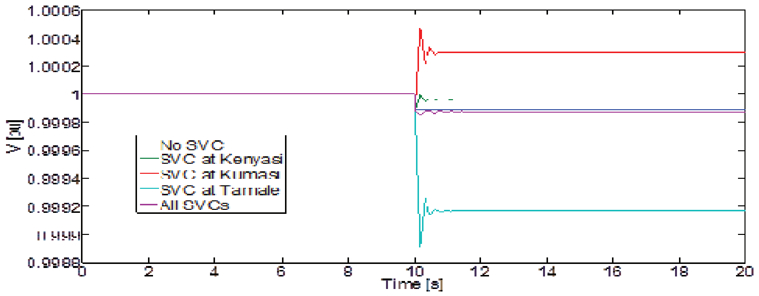
Fig. 6.11. Voltage profile for time domain simulation with one Aboadze generator outage Bus 12801 (b) Bus 14002 (c) Bus 1412



(a)



(b)

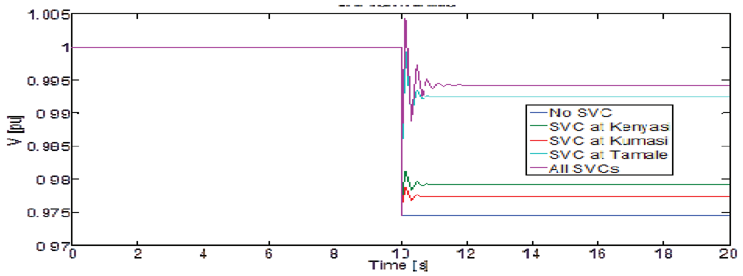


(c)

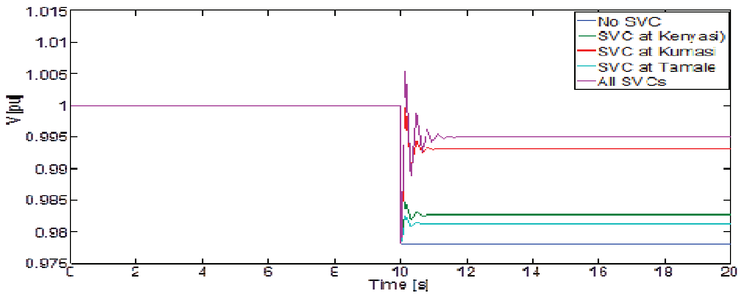
Fig. 6.12. Voltage profile for time domain simulation with one Bui generator outage
(a) Bus 12801 (b) Bus 14002 (c) Bus 1412

6.5.2 Line Trip

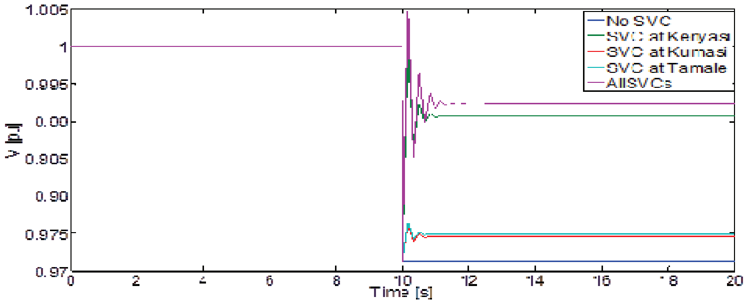
In the same vain as that of the generator contingency, the effects of three line trips out of the eleven scenarios analyzed are presented.



(a)



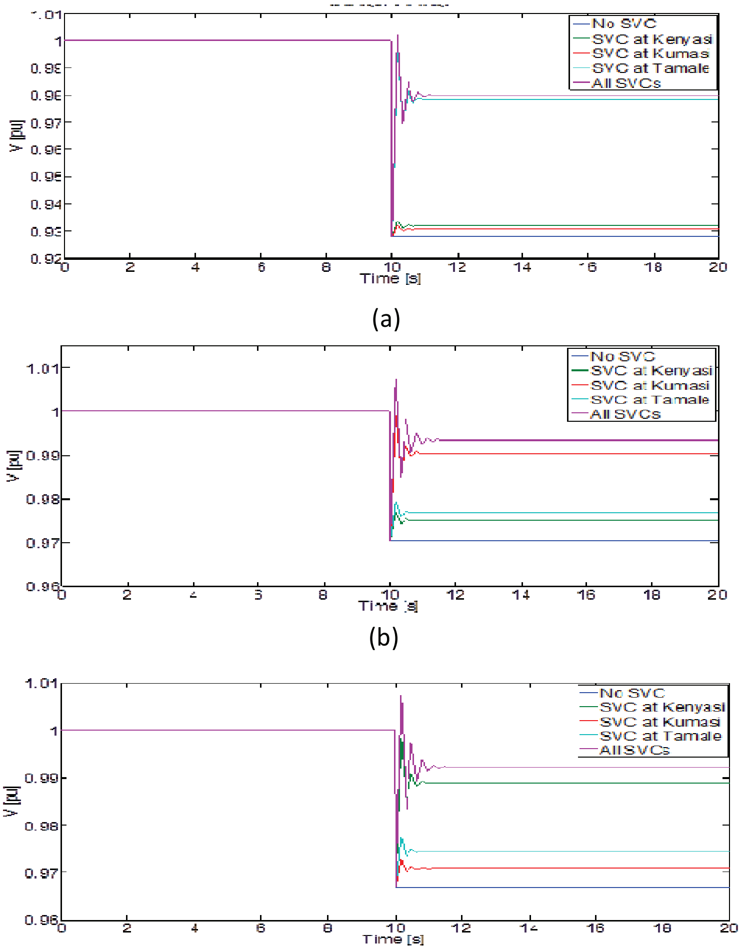
(b)



(c)

Fig.6.13. Voltage profile for time domain simulation with line BUI 1550- KIN1920-161kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

These are; 1550Bui-1920KIN (161kV), 1921KIN-1297BOLGA (330kV) and 1921KIN-14001PRK2BSP (330kV). The lines were tripped during time domain simulation at time t=10sec and total simulation time of 20sec.



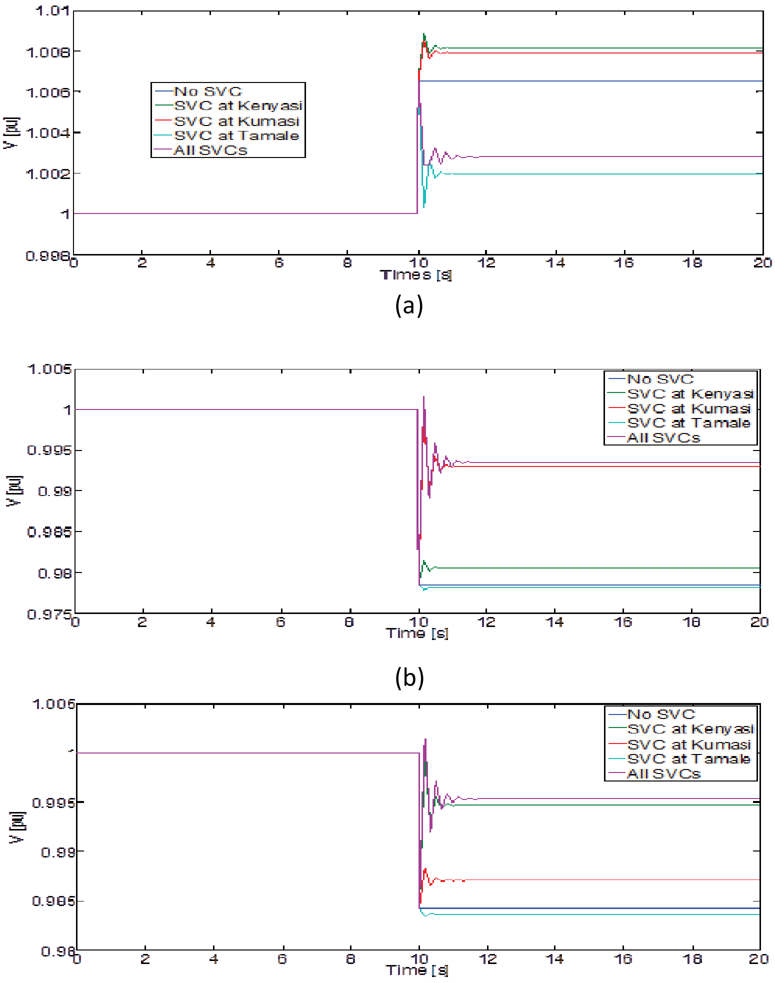
(a)

(b)

(c)

Fig.6.14 Voltage profile for time domain simulation with line KIN 1921-BOLGA 1297-330 kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

These trips were located at the south (Kumasi), one at the middle belt (Kintampo) and the last at the north (Bolga). The time domain simulation results obtained are as presented in figures 6.13 – 6.15.



(a)

(b)

(c)

Fig.6.15 Voltage profile for time domain simulation with line KIN 1921 - PR K2BSP 14001-330 kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

The system becomes more voltage stable with the installations of the SVCs. The regions that are most unstable and lead to possibly voltage instability are the region beyond Bolgatanga and the 69kV line from Ho to Kadjebi.

Under line and generator trip contingencies, the SVCs complement each other when the source of the contingency is either in the north or at the south. A generator trip at the Bui power plant or a line trip around Kintampo all in the middle belt results in the SVCs reacting against each other. The SVCs at Kumasi and Kenyasi act in opposition to that of Tamale with the Kenyasi one having the most negative effect, all the same their total effect is positive making the opposing interaction less significant. It is recommended that in the light of the fast rate of voltage decay on the 69kV line it should be upgraded to 161 KV

7. Summary of Expansion Plan and Reactive Compensation

The preliminary input to this research work was the committed, proposed and/or planned by both the Ghana Grid Company and the West African Power Pool. These included generation, transmission expansion and major customers/rural electrification projects. Alternative configurations were designed for the selected years. Power flow, selective N-1contingencies, CPF and static voltage stability analysis conducted using the 2010 configuration as the base. Reactive compensators were injected in the best performed configurations for them to meet all the criteria for reliable and stable system.

Areas that exhibited major system inefficiencies were the Tamale-Bolgatanga, Ho-Kpandu and Dunkwa-Asawinso leading to critical voltage collapse. In attempt to make these areas more voltage stable, parts of the long redial line of the northern sector were closed into mesh networks, the Ho-Kpandu line uprated to 161kV and recommended that it is linked to the Yandi bus in the future and reactive compensators used to stabilize voltages at the western corridor.

Based on the proposed WAPP 330kV interconnections backbone, the major generation plants were interconnected at 330kV level and linking the south to the north. Having assessed the system as mentioned above, the next stage was to assign the developmental plan to specific years so as to achieve the targeted configuration of 2020, ensuring system voltage stability and reliability.

The breakdown of the plan is as presented here below:

2011:

- Construct Sunyani-Mim line
- Provide access to hook Asogli plant to the Grid
- Upgrade Tafo-Nkawkaw line
- Corresponding compensation

2012:

- Supply load at Sonabel
- Construct Bolga-Kintampo 330kV line
- Break into Techiman-Tesilima line at Tesilima and construct 2 no. Bui-Tesilima
- Create Bulk Supply Point at Kumasi and construct Kumasi-Kintampo 330kV line
- Link BSP at Kumasi and existing Kumasi substation
- Break into Techiman-Tamale and insect 330kV substation at Kintampo
- Construct Bui-Kenyasi line

2013

- Construct Ghanaian part of the Bolga-Ouga 225kV line
- Create BSP at Accra and uprate Achimota-Winneba line
- Upgrade Aftap-Dcem line
- Install SVC at Tamale
- Construct Kumasi-Prestea 330kV line
- Construct second Kumasi BSP and link to the first

2014

- Close Bolga-Sawla loop through Tumu, Wa and Azu Mines
- Construction of Tamale-Kintampo through Atebubu
- Construct Volta-Lome 330kV line
- Create substation at Sowutuom on the A boadze-Volta line
- Construct new substation at Tema and hook Valco and Asogli plant to it.
- Construct Bonyere-Essiama, Bonyere-Prestea and Bonyere-Elubo

2015

- Install SVC at Kumasi
- Link Wa-Tumu line to improve voltage stability
- Parallel Tamale-Bolga line
- Break into Aboadze-Prestea and create new substation at Tarkwa

2016

- Construct OPB substation
- Construct Bonyere-OPB 161kV line
- Construct OPB and Elubo

2017

- Hook Sei generation plant to New Tema substation (Smelter II)

- Solve emerging operational problems
- In cooperate new development

2018 to 2020

- Solve emerging operational problems
- In cooperate new development

To ensure that the system is voltage stabilized and reliable, compensation were made at various points in time. Table 7.1 present the compensation level of 2010 and 2020.

Table 7.1 Base Peak Load Reactive Compensation in per unit values

BUS NAME	2010	2020	BUS NAME	2010	2020
2010-ABOBO	-	0.100	1911-N-ABIREM-LV	-	0.216
1200-ASAWINSO	-	0.400	3010-LOME0	0.100	0.100
1050-ACHIMOTA	0.400	1.000	10313-VALCO	0.200	0.200
1130-KUMASI	0.900	0.900	10312-VALCO	0.200	0.200
1120-OBUASI	0.120	0.120	1400-K2BSP	-	0.432
1210-N-OBUASI	0.240	0.240	1040-TEMA	0.116	0.116
1260-TECHIMAN	0.250	-	1060-WINNEBA	-	0.200
1280-TAMALE	0.020	-	1090-TARKWA	-	0.100
19501-AZ-LV	-	0.100	1226-KADJEBI	-	0.150
1020-VOLTA	-	0.550	1220-ASIEKPE	-	0.100
4010-SONABEL	-	0.010	1100-PRES-161	0.320	0.320
1270-SUNYANI	0.096	0.096	1413-KENY-LV	SVC	SVC
1370-MALLAM	0.300	0.193	14002-KSI-SVC	-	SVC
1910-N-ABIREM-HV	-	0.550	12801-TAM-SVC	-	SVC
10314-VALCO	-	0.200			

8. Recommendation and Suggestions for Future Studies

Analysis to assess the static stability had been carried out on the selected intermediate and the mid-period years (2010, 2012, 2014, 2015, 2016, 2018, 2020). Although, the various configurations had proven to be quite stable under static conditions the rating of the already installed SVC at Kenyasi should be increased to 60MVr and 60 MW for the reactive and active power respectively. Also the Voltage corridor should be upgraded to 161kv and be connected to the Yendi bus to improve on its voltage.

To fully assess the performance of the configurations, a complete dynamic analysis is to be carried out to ascertain their dynamic behaviour with respect to transient disturbances and also coordination between dynamic components of the systems.

Investigation into the possibility of injecting a power plant, preferably solar or wind power around Tamale and Bolgatanga to improve on voltage stability is recommended.

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List of candidate’s work related to this doctoral dissertation

Articles in Impacted Journals:

[1] Joseph Eminzang ESSILFIE, Josef TLUSTY, Pavel SANTARIUS. “Using SVC to Improve Voltage Stability of the Ghana Power Network”, Przeglad Elektrotechniczny, Accepted on December 6, 2012 with registration no. PE3570

[2] Joseph Eminzang ESSILFIE, Josef TLUSTY, “ Evaluation of the effects of the proposed STATCOM installation at Tamale, Ghana on Voltage Stability”, Przeglad Elektrotechniczny (In Press)

Reviewed Journals: -

Patents: -

Publication listed in WOS:-

Other Papers:-

List of candidate’s work not related to this doctoral dissertation

Articles in Impacted Journals

[3] Essilfie J. E, Aggrey G. K., “design and implementation of Takagi-Sugeno type of fuzzy logic controller for STATCOM”, Journal of the Ghana Institution Of Engineers, (In Press)

[4] Aggrey G. K, Simon Anthony, Ayebi-Arthur K, Essilfie J. E and Attachie J,” Distortion analysis of the sub-band coder”, Journal of the Ghana Institution Of Engineers Vol. 7&8 No.1, 2011, pp33-38

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Patents: -

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[5] Joseph Eminzang Essilfie and Josef Tlusty. Voltage Dip Mitigation Using FACTS Controllers, Focus – Tarkwa Mining
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No response and reviews

The authorship quotient of publications started here in above is equally divided into the mentioned authors

Summary

The effects of the fast growing Ghanaian economy on her power system and also demand had been taken into consideration under this work. The situation is aggravated with the additional demand on the system as a result of the West African Power Pool projects which seeks to interconnect member states into a common power pool. For the WAPP project to succeed, Ghana ought to have a reliable, static and dynamic stability so as to support the energy balance equation of the sub region. A development plan spanning the period 2012 to 2020 had been suggested following a detailed static voltage stability analysis carried on all the suggested configurations of the various years. Recaps of the results of different analysis are made below.

Load flow analysis conducted on the selected networks shown that they are adequate for the forecasted base peak load scenarios. However, the 2010 scenario shown a reserve margin less than the capacity of all generators with the exception of those at SIE generation plant and as such could not support N-1 contingency. Similarly, the final 2020 network also has a reserve of 70.377MW meaning that it could not support N-1 contingency.

In the case of the low peak load scenarios, the systems proved resilient with SVCs compensation range of -50MVar to 40MVar for the two proposed SVCs at Tamale and Kumasi.

The high peak load cases reveal that generation was not enough to support N-1 contingency for the year between 2015 and 2020 since generation reserves were between 90MW and 148MW which is less than the capacity of any of the generators at Akosombo. In the case of 2010, the existing SVC at Kenyasi exceeds its maximum limit of 40MVar by 56.21% and a generation deficit of 121.06MW. The 2020 system loading requires an importation of 125.13MW to meet the load demand.

It is therefore recommended that arrangements are made to increase the available generation of 2020 by a minimum of 350MW to ensure reliability of the system at the forecasted high peak load condition under generation contingency situation.

From the sensitivity analysis it was clear that the Bolgatanga-Tamale area has the potential of becoming voltage instable. The 69kV line is a source of voltage instability. The participated buses are local, thus the buses affects themselves. It is therefore recommended that the line after it is converted to 161kv line be hooked to the Yendi load bus. This will put it in the ring to ensure voltage stability.

Small signal stability analysis revealed deficiencies in reactive power and was addressed throughout the system development. The limits of the installed and proposed SVCs were not able to sustain voltage stability during small signal disturbances of the system through the design period; therefore capacitors of the following power ratings were installed to support the SVCs: 0.1pu at Kenyasi, 0.216pu at Tamale and 0.6pu at Kumasi. In addition, the 69kv live in the Volta region is converted to 161kv and a 161kv line also constructed from Wa to Tumu.

Under TD simulation, the system proved more voltage stable with the installations of the SVCs. The regions that are most unstable and lead to possibly voltage instability are the region beyond Bolgatanga and the 69kV line from Ho to Kadjebi.
Under line and generator trip contingencies, the SVCs complement each other when the source of the contingency is either in the north or at the south. A generator trip at the Bui power plant or a line trip around Kintampo all in the middle belt results in the SVCs reacting against each other. The SVCs at Kumasi and Kenyasi act in opposition to that of Tamale with the Kenyasi one having the most negative effect. All the same their total effect is positive making the opposing interaction less significant.
It is recommended that in the light of the fast rate of voltage decay on the 69kV line it should be upgraded to 161 kV and be put into a ring.
Recommendations and suggestions for future studies had been made.

Resumé

Práce se zabývá rozvojem a optimalizací elektroenergetické soustavy vyvolané rychle rostoucí ekonomikou Ghany. Kromě samotného růstu domácí spotřeby bylo taky zváženo zatížení přenosové soustavy společným projektem „West African Power Pool" (dále jenom WAPP), jehož cílem je propojení energetických soustav zúčastněných států. Úspěšnost projektu WAPP zaručuje Ghana tím, že zabezpečí statickou i dynamickou stabilitu energetickcých sítí tak, aby byly požadavky celého regionu v rovnováze. V práci byl na základě detailní analýzy stability sítě realizované pro všechny navrhované konfigurace a roky navržen rozvojový plán projektu na léta 2012 až 2020. Rekapitulace těchto analýz je shrnuta níže.

Analýza výkonových toků provedená na uvedených sítích ukázala, že sítě jsou schopné vydržet předpovězené scenáře pro základní zatížení (*base peak scenarios*). Nicméně, analýza pro rok 2010 ukázala, že rezervní kapacita sítě je menší než kapacita všech generátorů s výjimkou těch instalovaných v elektrárně SIE, z čeho vyplýva, že N-1 kontingence není zaručena. Podobně, N-1 kontingence sítě není zaručena ani ve finální podobě sítě z roku 2020, protože její výkonová rezerva je rovná jenom 70 MW.

V případě scénářů nízkého, či špičkového zatížení, bylo zjištěno, že systémy jsou odolné při použití SVC v rozsahu od -50Mvar do 40Mvar , přičemž se uvažují dvě instalace SVC a to v Tamale a Kumasi.

V případě scénařů velkého špičkového zatížení se ukázalo, že výroba elektřiny není v letech 2015 až 2020 schopná zabezpečit N-1 kontingenci. Důvodem je velikost výrobních rezerv, které se pohybují mezi 90MW až 148MW a jsou menší než kapacita libovolného generátoru v Akosombo. Když se zaměříme na rok 2010, tak dostáváme, že již existující SVC v Kenyasi převyšuje svůj maximální limit 40Mvar až o 56,21% , což představuje deficit 121 MW. V roce 2020 bude nutné importovat až 125 MW elektrické energie.

Z těchto důvodů je tedy doporučeno modifikovat projekt tak, aby byla výrobní kapacita v roce 2020 navýšena minimálně o 350MW. Tato změna pak zajistí spolehlivost systému i během těžce předvídatelných situací při velkém špičkovém zatížení sítě.

Analýza citlivosti ukázala, že potenciál napěťové nestability má hlavně oblast Bolgatanga-Tamale, přičemž zdrojem nestability je 69kV vedení. Toto vedení je připojené k lokálním systémům , které se navzájem výrazně ovlivňují. Situace může byt vyřešená změnou napětí vedení na 161 kV a jeho připojením k rozvodně Yendi, která pak zabezpečí napěťovou stabilitu.

Malá stabilita signála analýza odhalila nedostatky jalových výkonů, přičemž se doporučuje její přehodnocení v rámci celého projektu. Limity současných i plánovaných SVC nejsou schopné zabezpečit stabilitu napětí při nízkých odchýlkach signálu a to během celého období realizace projektu. Z tohoto důvodu bylo navrženo přidat podpůrné kondenzátory s příslušnými parametry v následujících místech: 0,1pu v Kenyasi, 0,216pu v Tamale a 0,6pu v Kumasi. Také bylo navrženo postavit nové 161kV vedení z Wa do Tumu a změnit původní 69kV vedení v regionu Volta na vedení 161kV.

Simulace TD potvrdila, že systém je napěťově stabilnější s instalacemi SVC. Oblasti, které jsou napěťově nejvíc nestabilními, jsou regiony za Bolgatanga a 69kV vedení z Ho do Kadjebi.

V případě neočekávaných událostí jak na straně elektrické přenosové soustavy, tak na straně elektráren, celou síť stabilizují systémy SVC nezávisle na místě vzniku neočekávané situace. Výpadek generátoru v elektrárně Bui, anebo porucha na vedení v blízkosti Kintampa, oboje v oblasti centra zásobované oblasti, vyustí v aktivaci systému SVC, který eliminuje následky těchto událostí. SVC v Kumasi a Kenyasi působí proti SVC v Tamale, přičemž nejvíce negativní efekt má SVC v Kenyasi. Podstatné ale je, že jejich společný efekt na síť je pozitivní. Na základě simulace lze také doporučit, aby 69kV vedení byla přestavěna na 161kV vedení.

Práce obsahuje také doporučení a návrhy budoucích studií na dané téma.