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Using SVC to Improve Voltage Stability of the Ghana Power Network

***Abstract**. This paper forms part of an ongoing system development of the Ghanaian power network. Preliminary studies have shown that the northern sector is venerable to voltage instability which has led to the proposed installation of STATCOM at Tamale. It is therefore necessary to assess the performance of the device when put in operation. Comparison had therefore been made between the use of STATCOM and Fixed Compensator. Line and generator contingencies as well as small signal disturbances analysis had been carried out. Voltage stability is improved with the installation of STATCOM as well as reduction in voltage oscillation during transient. Loadability limit of the system is also increased. Further evaluation targeted at the inter-tie with Burkina Faso has been proposed*

***Streszczenie.** W artykule opisano prace nad rozwojem sieci elektroenergetycznej Ghany. Badania wstępne wykazały, że północny sektor sieci jest wpływa na niestabilność napięcia. Jako rozwiązanie zaproponowano instalacje kompensatora STATCOM. Dokonano jego porównania z klasycznymi filtrami biernymi, zarówno pod kątem potencjalnych awarii w sieci, jak i niewielkich zakłóceń. Proponowane rozwiązanie zwiększa stabilność napięcia oraz możliwości obciążeniowe. (**Zastosowanie kompensatora SVC w stabilizacji napięci w sieci elektroenergetycznej Ghany**).*

Keywords: *Static Var compensation (SVC), Voltage stability, Contingency, Fixed compensation, Loadability*
Słowa kluczowe: kompensator bierny mocy (SVC), stabilność napięcia, przewidywanie, kompensacja statyczna, obciążalność.

Introduction

The Ghanaian power system network in recent years have undergone massive expansion and it is still ongoing, also the West African Power Pool project further increases the demand on interconnections and for that matter the availability and reliability of the networks of member countries.

Ghana is interconnected with all her three neighbouring countries namely; Burkina Faso, Togo-Benin and La Cote D'Iviore. Preliminary studies have shown that there is insufficient reactive power in the system to accommodated system disturbances leading to a number of partial and total blackouts experienced in Ghana in recent times. It is therefore important that causes of these power outages are determined and addressed.

There are two methods based on bifurcation theory for determining voltage collapse point, continuation and direct methods. These two techniques identify the system equilibrium point where the power flow Jacobian is singular [1-3].

Voltage instability had been identified are the result of insufficient reactive power in a system so as to support load changes as the loading of the system approaches it loadability limit. When the increase in loading is not checked, voltage decays to a non recovery level which is termed as the voltage collapse point or the loadability limit. The only way to prevent this is to inject reactive power to balance the generation-load reactive power equation, thus maintaining equilibrium state of the system.

Traditionally utilities have used fixed compensators (fixed capacitor and fixed inductor) to support the reactive power demand of power systems. This method of reactive power compensation is becoming lesser and lesser relevance in today's power system as a result of the nature of modern loads. A fast acting and variable source of reactive power compensation is therefore required.

Flexible A C Transmission system (FACTS) controllers have proven to provided the needed reactive power at the appropriate time and also introduce flexibility in the operation of the system. FACTS controllers are categorized into two groups, the thyristorized and inventor based controllers. The major difference between them is the rate of responds to transient conditions since they are virtually the same under steady state conditions. In this article, the issue of static voltage stability is dealt with; hence SVC is implemented for voltage stability enhancement

Shunt Compensation

Assuming that, a pure capacitor is connected at the mid-point of a line as shown in fig.1, such that the sending, receiving and mid-point voltages are the same in magnitude. Where V_{SM} and V_{MR} are the mid-point values for the sending and receiving ends segments of the line whereas I_{SM} and I_{MR} are the respective currents.

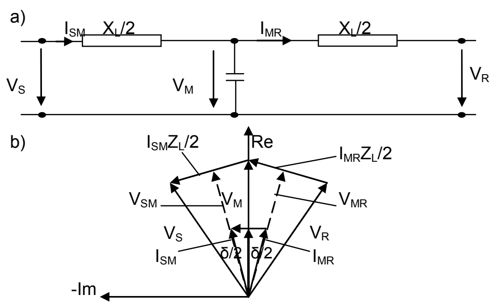


Fig.1. (a) Equivalent circuit with midpoint capacitive compensation (b) Phase diagram of voltages and currents

From the phasor diagram, it can be derived that;

(1) $$V_{SM} = V_{MR} = V\cos{\delta/4}$$

(2) $$I_{SM} = I_{MR} = I = \frac{4V}{X_L}\sin{\delta/4}$$

where: V_{SM}, I_{SM} - sending end mid voltage and current, V_{RM}, I_{RM} receiving end mid voltage and current, V – voltage, I – current, δ - load angle.

The transmitted power can also be stated as;

(3) $$P = V_{SM} I_{SM} = V_{RM} I_{MR} = V_M I_{SM}\cos\left(\delta/4\right) = IV\cos{\delta/4}$$

Alternatively,

(4) $$P = \frac{2V^2}{X_L}\sin{\delta/2}$$

and

(5) $$Q = VI\sin\left(\delta/4\right) = \frac{4V^2}{X_L}\left(1-\cos{\delta/2}\right)$$

From equations (4) and (5) there is clear evidence of the dependence of real and reactive power on the load angle of a line compensated at the mid-point. Both magnitude and direction of the load angle is of concern since it determines the nature of voltage instability, either low or high voltage instability. Depending on the system condition at a point in time the compensation requirement may be either inductive or capacitive.

Power System Stability

Power system stability has been recognized as a vital and important issue for a reliable and secure interconnected power system operation as far back as the 1920s. The importance of stability problem associated with power system operation arises from increasing power exchange between the constituent parts of a large interconnected power system.

There is the necessity of assessing the stability of large power systems and maintaining an adequate level of system security to minimize the risk of major blackouts resulting from cascading outages emanating from a single disturbance. The main requirement of system stability is to keep the synchronous operation of power system with adequate capacity and fast reaction to meet the fluctuations in electric demand and changes in system topology.

Successful operation of a power system depends largely on the ability to provide reliable and uninterrupted service to all loads and supply the required amount of loads by the available facilities [4].

The concern is the behaviour of the power system when it is subjected to transient disturbances. If the oscillatory response of a power system during the transient period following a disturbance is damped within acceptable time and the system can settle in a finite time to a new steady state, it is considered stable [5].

The steady state operating condition of a power system is an operating condition in which all the physical quantities that characterize the system are considered constant for the purpose of analysis [6].

The instability of power system might be characterized by different ways dependent on the system configuration, the nature of events and the system modes.

Mathematical representation of power systems

Power system can be represented by its [7] differential-algebraic set of equations of the form;

(6) $\overset{*}{x} = f(x, y : \lambda)$

(7) $0 = g(x, y : \lambda)$

where $x \in R^n$ represents the differential state variables, $y \in R^m$ represents the algebraic state variables and $\lambda \in R^p$ is a vector of real parameters which are responsible for voltage collapse.

Equation (6) can be reduced to

(8) $\overset{*}{x} = s(z, \lambda)$

The system of equation (8) shows a saddle bifurcation at the point of equilibrium $0 = s(z_0, \lambda_0)$, if the Jacobian $D_Z s(z, \lambda)$ has a unique zero eigenvalue and with normalized left and right eigenvectors *w* and *v* respectively, thus;

(9) $w^T D_Z s(z_0, \lambda_0) v = 0$

(10) $w^T \frac{ds}{d\lambda}(z_0, \lambda_0) v \neq 0$

(11) $w^T \left[D_Z^2 s(z_0, \lambda_0) v \right] v \neq 0$

Equations (9-11) describe the behaviour of the system near bifurcation point and hence are used to determine voltage collapse points [8].

Configuration of SVC

There are basically two types of Static Var Compensators namely:

- Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)
- Thyristor Switched Capacitor - Thyristor Controlled Reactor (TSC-TCR).

TSC-TCR is more flexible than FC-TCR and requires smaller rated reactor and consequently generates less harmonics.

The schematic diagram of a TSC-TCR type SVC is shown in fig. 2. Both TCR and TSC are connected on the secondary side of a step-down transformer.

Tuned and high pass filters are also connected in parallel which provide capacitive reactive power at fundamental frequency. The voltage signal is taken from the high voltage SVC bus using a potential transformer.

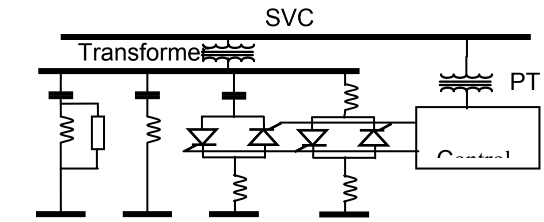


Fig. 2. Configuration of SVC (TSC-TCT Type)

The TSC is switched in using two thyristor switches (connected back to back) at an instant in a cycle when the voltage across the valve is minimal and positive resulting in minimal switching transients. In steady state, TSC does not generate any harmonics.

To switch off a TSC, the gate pulses are blocked and the thyristors turns off when the current through them fall below the holding currents. It is to be noted that several pairs of thyristors are connected in series as the voltage rating of a thyristor is not adequate for the voltage level required. To limit the rate of change of current in a TSC it is necessary to provide a small reactor in series with the capacitor.

Thyristor Switched Capacitor

At the time of switching if the voltage across the capacitor is zero or far less or more than the system voltage, a large surge current will flow through the capacitor. On the other hand if the voltage across the capacitor is equal the system voltage a finite current equal to the steady state value will flow through the capacitor. The rate of change of the capacitive current can be far more than the rating of the capacitor and will there damage it.

To protect the capacitor from damage an amount of resistance is connected in series with the capacitor.

If the system voltage across the capacitor is given as;

(12) $v(t) = \sqrt{2} V \sin(\omega_o t + \alpha)$

and switched on at $t = 0$, then with initial condition of $i(0) = 0$ and $v_c(0) = V_{C0}$ the capacitor current can be expressed as:

$$i(t) = \sqrt{2} I_{AC} \cos(\omega_0 t + \alpha) -$$

(13) $$nB_C \left[V_{C0} - \frac{n^2}{n^2 - 1} \sqrt{2} V \sin\alpha \right] \sin \omega_n t$$

$$- \sqrt{2} I_{AC} \cos\alpha \cos \omega_n t$$

where:

(14)

$$\omega_n = n\omega_0 = \sqrt{\frac{1}{L(t)C(t)}},\ n = \sqrt{\frac{X(t)_C}{X(t)_L}},\ B(t)_C = \omega_0 C(t) = \frac{1}{X(t)_C},\ B(t)_L = \frac{1}{X(t)_L}$$

(15) $$I(t)_{AC} = \frac{VB(t)_C B(t)_L}{B(t)_L - B(t)_C} = \frac{VB(t)_C n^2}{n^2 - 1},$$

Note to equations 14 and 15: The (t) only indicate that the values changes at a point in time during operation and not a function of time.

In practice the reactor is so selected that *n>3*.
Equation (12) is arrived at with the assumption that resistance is negligible.

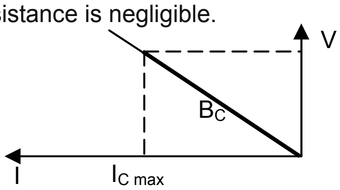


Fig.3. Operating V-I area of the TSC

When resistance is considered, the last two parts of the equation which forms the transient portion of the current will decay. It can also be seen that the current is proportional to the applied voltage based on the admittance of the capacitor as illustrated by the V-I plot in fig. 3. The maximum applicable voltage and the corresponding current are limited by the ratings of the TSC components.

Thyristor Controller Reactor

The instantaneous current through the reactor can be continuous ranging from zero to maximum possible value base on the circuit parameters. The magnitude is controlled be the firing angle α which can be between 0^0 and 180^0. The instantaneous current can be expressed as:

(16) $$i_{TCR} = \frac{\sqrt{2}V}{X_L} (\cos\alpha - \cos\omega t) = 0,$$

for: $$\begin{pmatrix} \alpha < \omega t < \alpha + \sigma \\ \alpha + \sigma < \omega t < \alpha + \pi \end{pmatrix},$$

where: V - applied *rms* value, X_L - reactor reactance of the fundamental frequency and σ - conduction angle and relates to the firing angle as: $\sigma = 2(\pi - \alpha)$

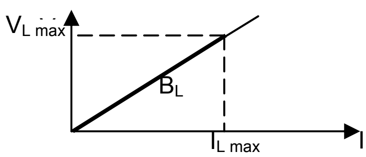


Fig. 4. Operating V-I area of the TCR

It is a known fact that at any delay angle α, an effective admittance B_L which determines the value of the current that will flow through the TCR at a given applied voltage.

In practice the magnitude of the current for a corresponding applied voltage is determined and limited by the power components of TCR. Thus, practical TCR can be operated anywhere in a defined V-I area, the boundaries of which are determined by its maximum attainable admittance, voltage and current ratings as illustrated in fig.4. It also illustrate that current is linearly proportional to the applied voltage.

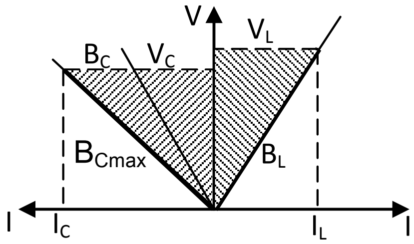


Fig.5. V-I area of the TSC-TCR type of SVC

To meet the reactive power demand on the SVC connected to the system, there can be more than one TSC connected in parallel. For this reason the total V-I operating area of the SVC considering a TSC-TCR SVC type with more than on TSC is as shown in fig. 5.

Description of Study System

The proposed 2015 network configuration of the Ghanaian power system network is made up of 142 bus, 133 lines, 72 transformers, 36 generators, 61 load centres and three FACTS shunt controllers at Kenyasi, Kumasi and Tamale. The SVC at Kenyasi is an end user device whiles the remaining two are transmission devices.

The system is interconnected with that of the neighbouring countries at four points namely; Abobo with La Cote D'ivoire, Elubo with Togo-Benin and at Bolgatanga with two points with Burkina Faso.

The connection with the isolated load in Burkina Faso and the Togo-Benin network are considered to be part of the main circuit due to their size. The remaining Burkina Faso and La Cote D'ivoire networks are represented by their equivalent networks fig.6.

Deviation from actual system

In order to examine the performance of the SVCs under dynamic conditions in comparison to a fixed compensator, fictitious fixed compensators are connected to the SVC buses to take over the functions on the SVCs and allow it to float under steady state operational condition.

Numerical Analysis

Power Systems Analysis Toolbox (PSAT) is an open source Matlab based software package for analysis and simulation of power systems. It is purposefully designed for teaching and research work. PSAT is convenient tool for static and dynamic analysis and design and control of power systems. It is facilitated to perform power flow, continuation power flow, optimal power flow, small signal stability analysis (Eigen value analysis), N-1 contingency analysis and time domain simulation.

Different types of graphical representation of results are also available [9,10].

FACTS controller models are implemented in PSAT making it very useful in modern day power systems research work. The type 1 SVC model implemented in PSAT which assumes a time constant regulator and with an anti windup limiter to lock the reactance at its assigned limits if they are exceeded is employed for this work.

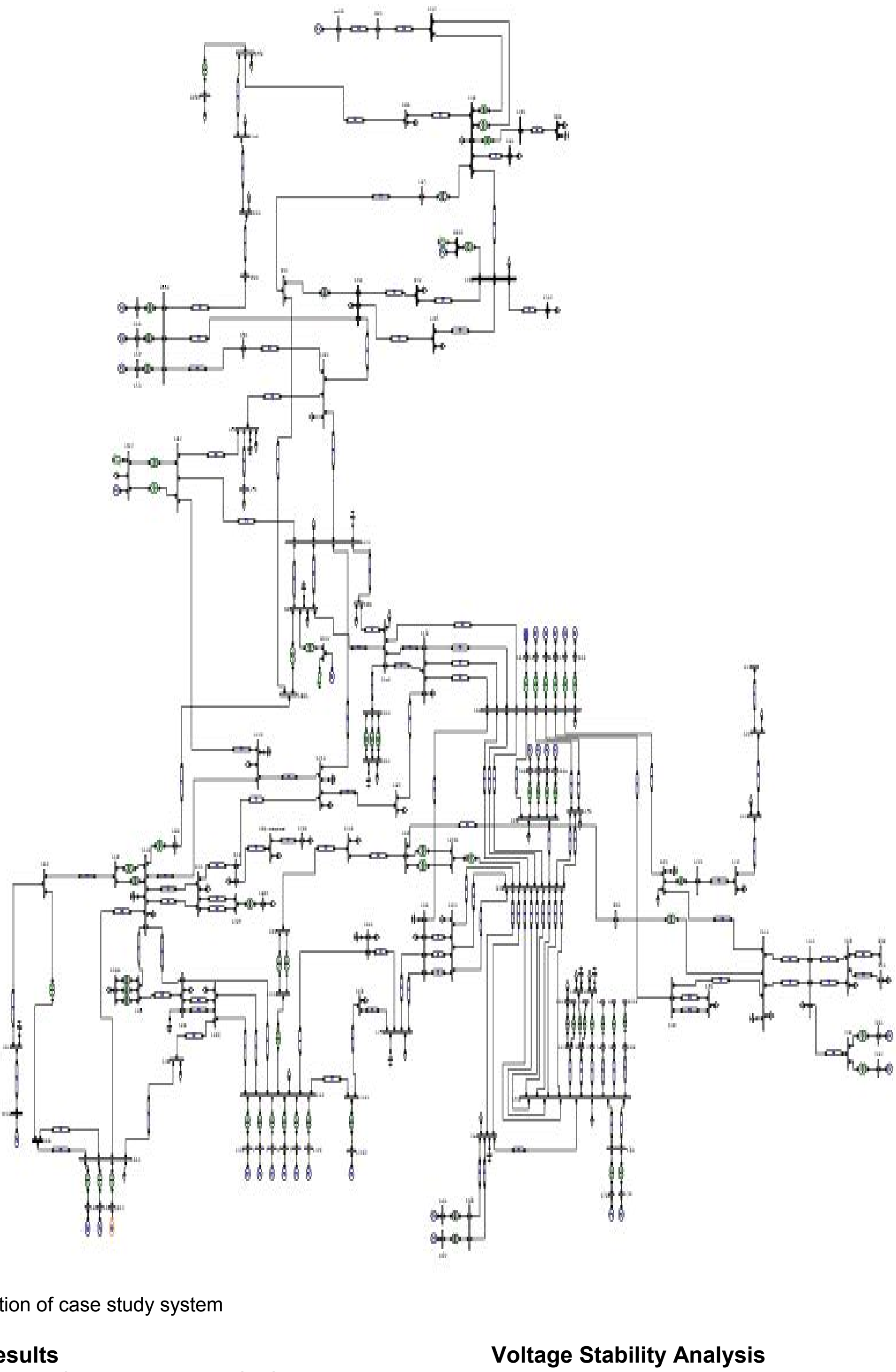


Fig.6. Configuration of case study system

Simulation Results

The system performance when SVCs are connected and without it but, with a fixed compensation is compared. The two configurations were simulated with the continuation power flow routine to assess their loadability limits under normal, generator and line contingency conditions. Likewise, time domain was run under two scenarios; generator and line contingencies.

Tables 1&2 presents the voltage profile of selected major load buses and the reactive power losses under normal operating conditions. The voltage profile of the normal conditions are the same since the SVC were replaced with fixed compensators of the same reactive powers as that of the SVC under normal circuit steady state condition.

Voltage Stability Analysis

Small signal Stability (PV Analysis)

As mentioned earlier, the two scenarios were made to operate under steady condition with similar voltage levels. System voltage stability was assessed by increasing the system loading level up to the maximum loadability point at which voltage collapse occur *(IEEE/PES (August, 2002))*. Four scenarios were considered under this.

First, CPF was run under normal operating conditions and then under three generator contingency situations for both system configurations.

The contingency situations were simulated with one of the generators disconnected at the three major generating plants namely; Akosombo, Aboadze and Bui. The results obtained for buses with three highest and lowest voltages are as presented in figures 7 to 10.

a)

b)

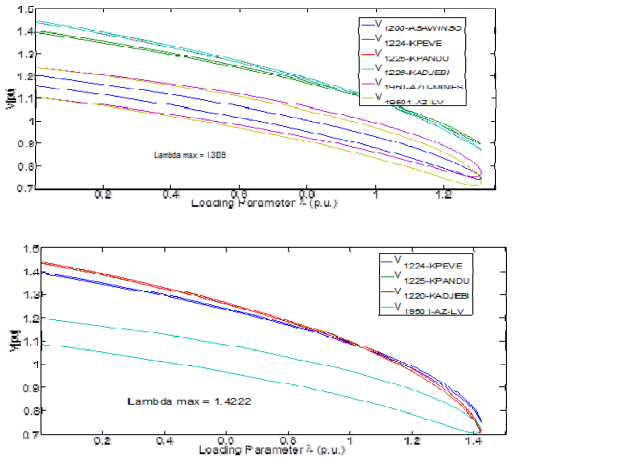


Fig. 7. Normal condition nose curves for some significant load buses (3 highest and 3 lowest voltages) (a) Without SVC (b) With SVCs

a)

b)

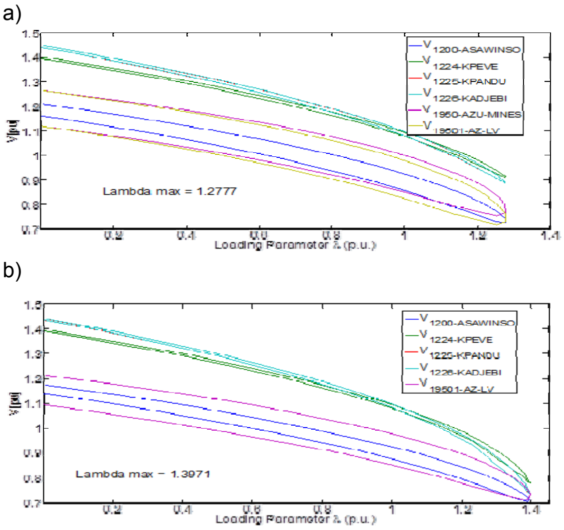


Fig. 9. Bui generator contingency condition nose curves for some significant load buses
(3 highest and 3 lowest voltages). (a)Without SVC (b) With SVCs

a)

b)

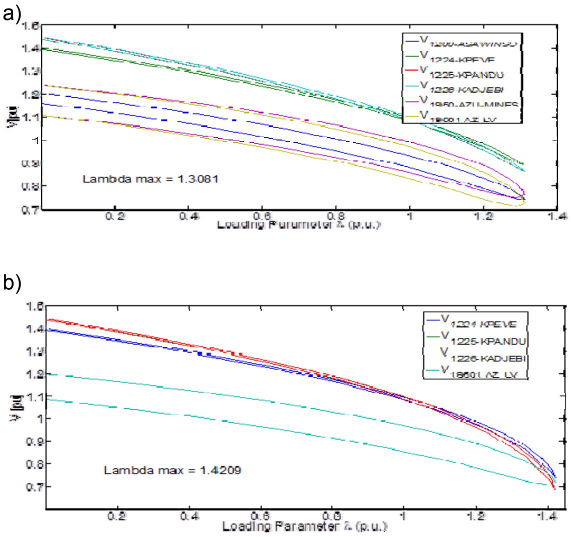


Fig.10. Aboadze generator contingency condition nose curves for some significant load buses (3 highest and 3 lowest voltages) (a) Without SVC (b) With SVC

It is clear from the graphs that, the configuration with SVCs have a higher loading factor (λmax) than the configuration without SVC under all the scenarios considered.

The loadability limits were increased to an approximated range of 10% - 12% of that of the configuration without SVC. From all the graphs, the 69kV line from Ho to Kadjebi presents itself as the weakest portion of the network in terms of voltage stability as it has a high voltage at low loading level but drastically reduces with load increase finally leading to system voltage collapse.

The region beyond Bolgatanga is also quit voltage unstable. There is virtually no difference between the nose curves of the system with and with SVC, indicating that the installed SVCs do not regulate the voltages in that region.

Table 1. Normal condition voltage profile

BUS NAME	WITH SVCs
1400-K2BSP	1.0189
1040-TEMA	0.9986
1070-C-COAST	1.0043
1080-TAKORADI	1.0335
1090-TARKWA	1.0192
10951-NTAR-LV	0.9814
1130-KUMASI	1.0154
1200-ASAWINSO	0.9311
1210-N-OBUASI	1.0006
1270-SUNYANI	0.9917
1280-TAMALE	1.0243
1300-BOGOSO	1.0164
1328-SOWUTUOM	1.0598
1412-KENYA-LV	1.0000
1610-BONYERE	1.0305
1911-N-ABIREM-LV	1.0199
2010-ABOBO	1.0190
3010-LOME0	1.0338
4010-SONABEL	1.0813

Table 2 Power losses under normal operating conditions

TOTAL LOSSES	WITH SVCs
REAL POWER	0.78872
REACTIVE POWER	-2.57128

Time Domain Simulation

Under time domain simulation, six cases were considered – three line trips and three generator outages. The responds of the system at the compensated buses as well as the inter reaction of the SVCs among themselves were observed.

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.

Generator Trip Contingency

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 have a negative interaction resulting in under compensation and the Kumasi SVC causes over compensation at the Kenyasi bus. Graphical presentation of the time domain simulations are as shown in figures 11-13.

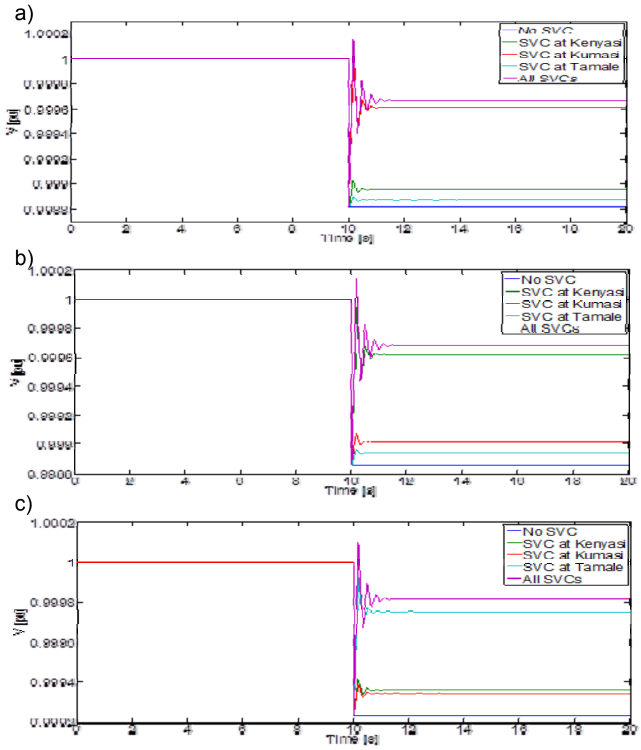


Fig.11. Voltage profile for time domain simulation with one Akosombo generator outage. (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

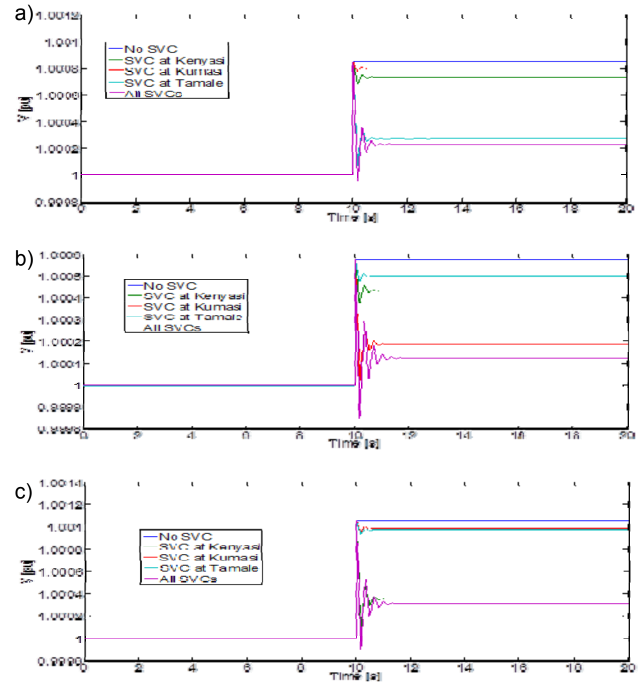
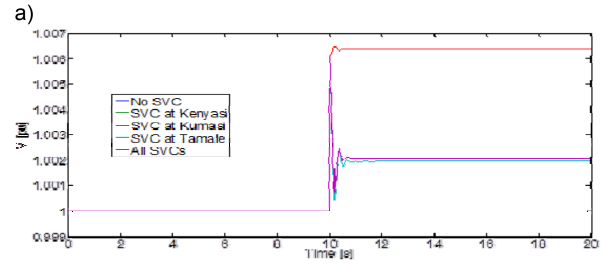


Fig. 12. Voltage profile for time domain simulation with one Aboadze generator outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412



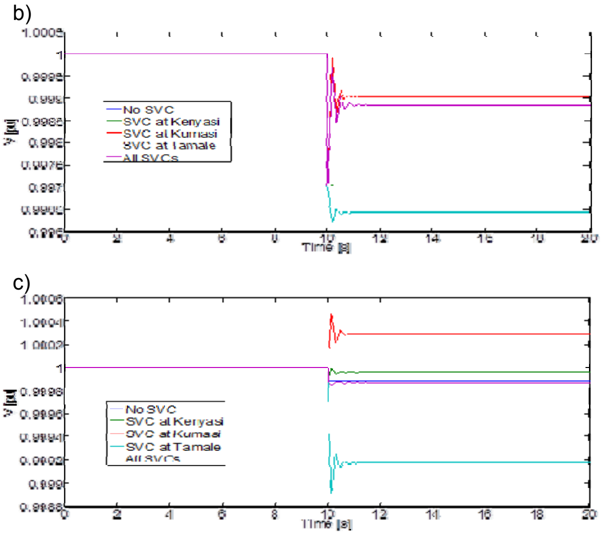


Fig. 13 Voltage profile for time domain simulation with one Bui generator outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

Line Trip Contingency

In the same vain as that of the generator contingency, the effects of three line trips were analyzed. 1550Bui-1920KIN (161kV), 1921KIN-1297BOLGA (330kV) and 1921KIN-14001PRK2BSP (330kV) lines were tripped during time domain simulation. 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 figure 14-16.

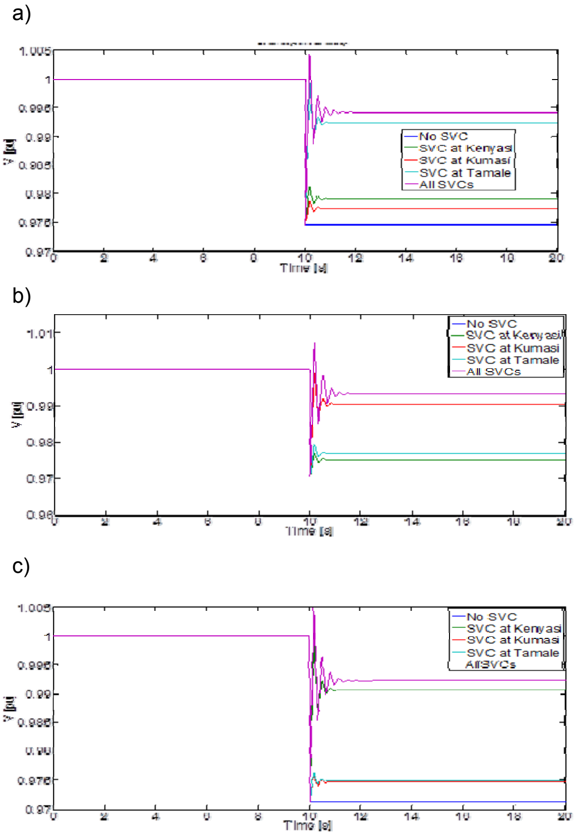


Fig.14 Voltage profile for time domain simulation with line BUI 1550- KIN1920-161kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

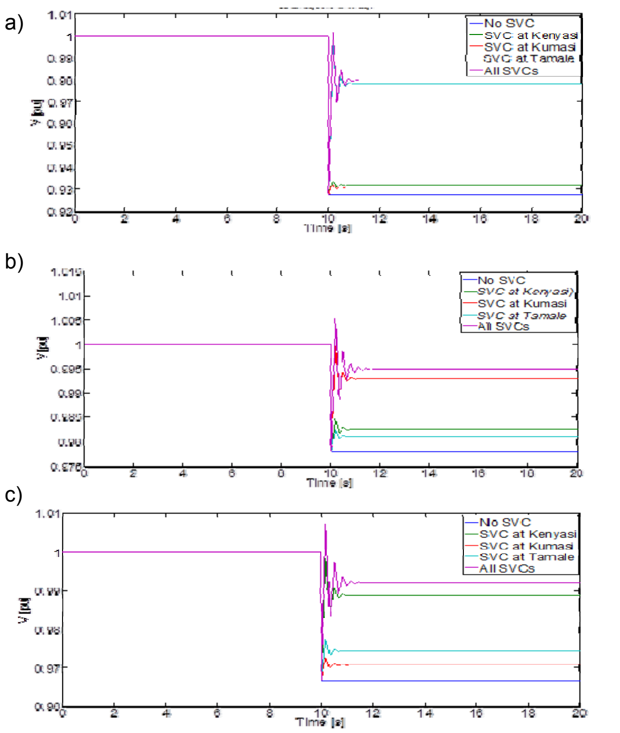


Fig.15. Voltage profile for time domain simulation with line KIN 1921-BOLGA 1297-330 kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

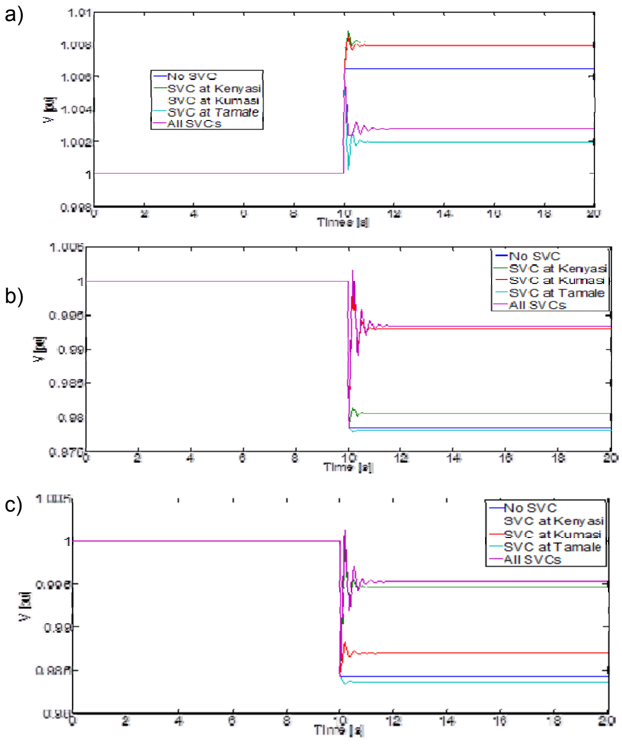


Fig.16. Voltage profile for time domain simulation with line KIN 1921 - PR K2BSP 14001-330 kV outage (a) Bus 12801 (b) Bus 14002 (c) Bus 1412

Conclusion

In this paper, voltage stability of the Ghana power systems network is studied without and with SVCs. The system becomes more voltage stable with the installations on 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 Kedjebi.

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. 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.

Further Work

The Authors recommend that further research work be carried out to arrive at the possibility of eliminating the negative interaction between the SVCs and also extend their benefit to the Bolgatanga area.

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