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DETERMINING LOCATION AND SIZE OF STATCOM TO ENHANCE VOLTAGE STABILITY OF POWER SYSTEMS FOR NORMAL AND CONTINGENCY SITUATIONS

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ABSTRACT

In power system, static voltage instability is becoming a serious issue of concern as the system continues to expand. The static voltage instability phenomenon comes about for two main reasons that is mismatch between loading and generation capacities and reactive power imbalance due to contingency. When the system is operating close to its Hopf Bifurcation point it is difficult to control the reactive power balance of the system hence any small disturbance can throw the system into unstable condition. The dynamics of modern systems demand a reactive power compensator that can response fast to changes in the system parameters and maintain the system in stable condition. In this paper, static voltage stability analysis had been carried out to determine the best location for Flexible AC Transmission System (FACTS) device installation to ensure static voltage stability under both normal and contingency conditions. The paper has verified that the weakest bus determined by eigenvalue and eigenvector analysis supported by continuous power flow and contingency analyses is the best location for Static Compensator (STATCOM) injection for static voltage instability control. The validity of a proposed algorithm is verified on a four base system serving Winneba-Kasoa-Swedru area of Ghana. The best location for STATCOM to control static voltage instability under normal and contingency conditions is determined to be the Kasoa bus. Based on the simulation results it is recommended that a fixed capacitor rated 40MVAr in combination of a STATCOM rating of 30MVAr is required for effective control under both normal and contingency situations

Keywords: FACTS, STATCOM, CONTINGENCY CONDITIONS, SADDLE-NODE BIFURCATION

INTRODUCTION

Bulk Supply Points and Primary Substations which used to serve load not too far away are now called upon to feed load at longer distances. The spread of the loads in most cases demand reactive power support that the original system can not provide. This has led to voltage instability in a lot of networks, and sometimes leads to either total or partial blackout due to lack of reactive power support. In some cases too, the transmission lines are operated very close or even beyond their loading limits due to excessive reactive power flow at the expense of active power transmission. Two main issues arise from this unpleasant system operation condition that is; high transmission losses and unaccepted low voltage levels are experienced. In the past, fixed compensation was used to solve these two problems. The nature and dynamics of today's load are such that the traditional fixed inductors and capacitors are not able to meet the dynamic requirements of modern networks. Due to technological advancement, the concept of Flexible Alternating Current Transmission Systems in short FACTS has made it possible to carry out reactive power compensation which meets the dynamic nature of the system.

The concept of FACTS first appeared in literature in 1989 when Narian Hingorani introduced it and defined it as the concept of using power electronics devices namely thyristors for power flow control at transmission level (Hingorani et al, 1999, Hingorani et al, 2000).

Recent developments in the area of power electronics had, made it possible to have a number of high voltage and current devices and have contributed to the area of research into FACTS controllers. These devices have the ability of fast switching. This property has resulted in the development of voltage source invertors having fast response, high reliability and wide operating range. (Morison et al, 2004, Baghaee et al, 2008, Gerbex et al, 2001, Di Santo et al, 2004)

The concept of FACTS devices has spread to cover distribution and customer end power quality management and reliability. FACTS devices are now used not only for power flow control but also for voltage instability, congestion, power reliability and harmonics issues.

All FACTS controllers provide controllability of series or shunt impedance on transmission and distribution lines or both depending on their purpose. Among these state of the art devices is the STATCOM which is a shunt compensator. For the purpose of voltage stability, STATCOM has been extensively used.

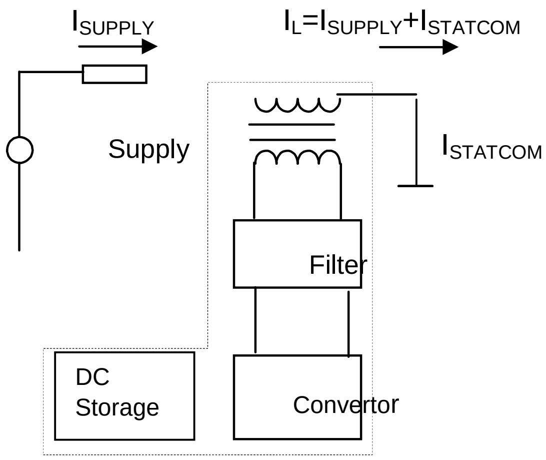

Fig.1a, Configuration of STATCOM

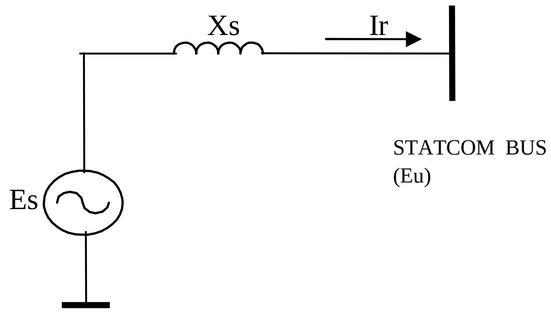

Fig 1b. STATCOM equivalent circuit

The current that STATCOM draws from the system can be divided into active and reactive components. STATCOM can control the line voltage at the point of its connection through regulation of reactive current injected or absorbed (Hingorani et al, 1999, Gyugyi, 1994, Gyugyi, 1990).

The benefit of installing any FACTS device could be fully realised when it is well located and adequately sized.

CONFIGURATION OF STATCOM

STATCOM basically consist of a voltage source converter, coupling transformer and a DC storage facility as shown in fig.1a. Filters are also (Chary et al, 2005) in-cooperated to manage the level of harmonics introduced into the system. It is to be noted here that in modern practice multiphase converters are employed in the design of converters in order to drastically reduce the harmonics injection. Therefore depending on the type of converter in use there may be the need for filters or not.

The use of converter and DC storage facility makes STATCOM have many advantages over the first order FACTS device - Static VAR Compensator (SVC).

The advantages are primary:

- Faster response
- Inherent modular and re-locatable
- It can be inter phased with power sources for active power control
- It is possible to increase the reactive current under transient condition if the elements of the VSI are so rated.
- Requires less space than SVC.
- It has superior performance under low voltage condition since reactive current can be maintained constant.

Consider that resistance is negligible as shown in fig.1b and E_s and E_u being the STATCOM internal and utility voltages respectively. The current exchange can then be expressed as:

$$I_r = \frac{E_U - E_S}{X_S} \qquad (1)$$

When, E_u is greater than E_s the invertors absorbs inductive power from the system on the other hand the invertors supplies capacitive power to the system. It is also clear that when the two voltages are equal the STATCOM will not exchange power with the system.

Controlling the phase shift between the STATCOM and system voltages, active power exchange can be realized. If the inverter voltage leads that of the system, active power from the STATCOM dc supply is feed into the system. On the other hand the system will supply active power to the STATCOM to recharge the dc storage.

From the “black box” viewpoint, the voltage-source converter type VAR generation can be considered a synchronous voltage source which will draw reactive current from the AC system depending on the external reference which may be varied in a defined range between the capacitive and inductive maxima, independent of the AC system.

Bifurcation and Static Voltage Instability

In a system of non linear property, slow change in parameters can lead to Saddle-Node Bifurcation (SNB) thus losing equilibrium. Figure 2, illustrated the dependence of bus voltage on loadability. Before the Hopf Bifurcation point (HB) the system is stable and

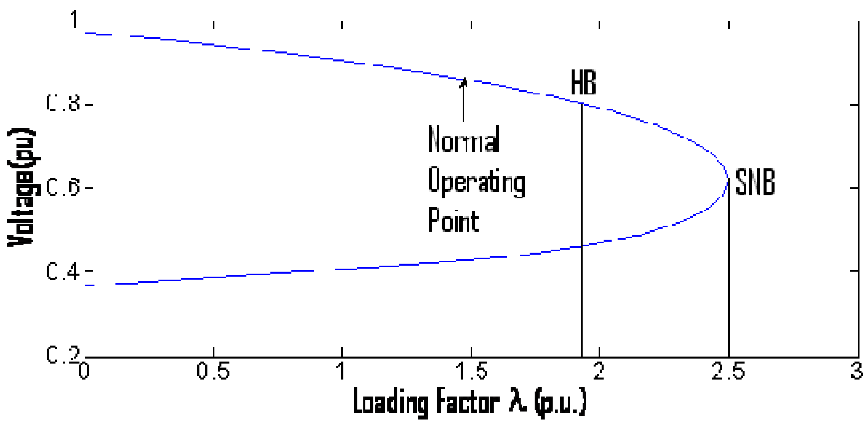

Figure 2. Saddle-Node Bifurcation and Hopf Bifurcation

between BH and SNB points the system will be transiting into an in-equilibrium state indicated as point SNB. Just before point SNB there are two voltage solutions to the instability problem, the solution for the upper curve results in stability whiles that of the lower curve leads to instability. At the point SNB, there exist only one solution and no solution exists beyond this point. The system can therefore be loaded up to the SNB without system collapse. The closer the loading point is to the saddle node bifurcation point the likelihood that small perturbation of the system can lead to static voltage instability. The horizontal distance between the normal system operating point and the SNB point is referred to as the margin to voltage collapse. For any network the longer the margin the stable the system is. To analyse any network level of static stability, a static model of static load flow equations could be solved at different loading points to determine the saddle node bifurcation point of the system.

Modal Analysis and Static Voltage Instability

In 1992, Gao, Morison and Kundar proposed the modal analysis which is dependant on the power flow Jacobian matrix. It deals with the computation of the smallest eigenvalues and their associated eigenvectors of the reduced Jacobian matrix resulting from a load flow solution. The eigenvalues associated with the node of voltages and reactive power variations gives a representation of proximity of voltage instability. The more positive the eigenvalue of a node, the more stable the node. A zero eigenvalue indicates that the node is at the verge of static voltage instability whiles a negative eigenvalue is an indication of static voltage instability. In addition, the participating factor associated with the weakest node gives a picture as to the extent the node is self responsible and to what extent other nodes are contributing to its weakness (Gao et al, 1992).

Contingency Analysis

Power systems are operated in a way such that overloads do not occur either in real time or under any sudden change (contingency) in system parameters. Contingency can be a lost or connection of transmission line(s), changes in generation or load. Any of the contingency situations can distort the reactive power balance of the system resulting in over or under voltage, over current and frequency violations. Any of the resulting state can lead to total or partial system collapse since, the generating plants are sometimes not able to cope with the dynamics of change as well as magnitudes. To maintain system security, the system should be able to response quick enough and also be able to generate or absolve the required reactive power at all times.

Determining the location of STATCOM Installation

The location for the placement of STATCOM is to be such that it influences effectively the voltage of the weakest bus as such it is placed at the bus responsible for the weakness of the weakest bus. The criteria for sizing the STATCOM is aimed at partially compensating reactive power to boost the voltage at the weakest bus and at the same time not resulting in the voltages of other buses exceeding the allowable limit.

There are a number of proposed methods of identifying the weakest bus for voltage compensation. Predominantly among them are base on load flow to determine the bus with lowest voltage and margin to voltage collapse. The power system is a complex interrelated system hence a change in one parameter will affect the whole network positively or negatively. It is therefore necessary to combine the various methods and to select the compensation bus that will ensure optimal performance of the system both in normal and contingency situations. In line with this a procedure to determine the optimal location of STATCOM is proposed in this paper. Under this procedure more than one weak bus are determine by the different methods and are graded based on the depth of their weakness. Compensation is then made at those buses separately and whole system performances are compared.

The methodology is summarized through the follows stages:

Step 1: Model the network on a simulink platform.

Step 2: Assign initial values of voltage magnitudes and angle to all PQ and Load buses.

Step 3: Run load flow and ensure that all values are within limits.

Step 4: Run CPF to determine the weakest bus or buses.

Step 5: Run Eigenvalue analysis to determine weakest bus and associated participation factors.

Step 6: Determine the weakest bus from steps 4 and 5.

Step 7: Connect the STATCOM to the selected weakest bus.

Step 8: Repeat steps 3-5 whiles making sure that no limit is violated and determine the appropriate STATCOM rating.

Step 9: Repeat step 8 with STATCOM placed at the next weakest bus

Step 10: Compare results obtained from steps 8 and 9 to confirm the best location.

Step11: Perform contingency analysis with the STATCOM connected to the finally selected bus and determine the optimal STATCOM rating.

Description of Test System

The electrical parameters of the test system of figure 3 are as given in Appendix 1. The system consist of a slack bus representing the I61KV supply from Gridco, two 161/33KV transformers, one 161KV bus, three 33KV buses, three lines and three loads. The system is an equivalent circuit representing the whole network serving Winneba-Kasoa –Swedru areas. Per unit parameters are at the base of 100MVA

Simulation Results and Discussion

Voltage Profile

Table 1 illustrates the voltage profiles for three scenarios

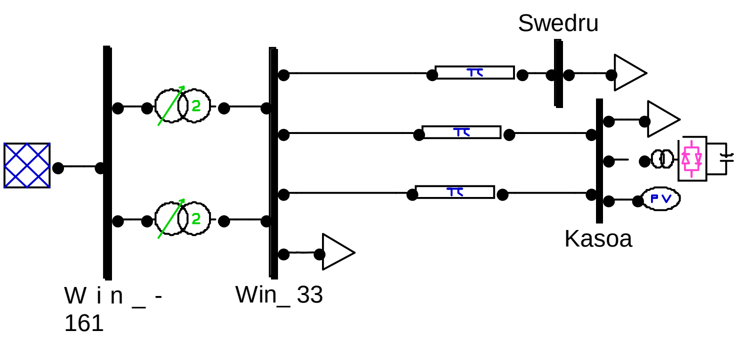

Figure 3. Test Network

that is, normal condition (base case), STATCOM installed at Kasoa busbar and STATCOM installed at Swedru busbar. Under the base case condition Kasoa bus recorded under voltage whiles the Swedru bus had a voltage slightly above the minimum limit of 0.9pu. In the case when the STATCOM was installed at the Swedru bus, Kasoa bus voltage improve to a value just above the minimum limit whiles in the case of STATCOM connected to the Kasoa bus all voltages were in the range of 1.02-1.05 pu.

From Table 2., it is indicative that generation of both active and reactive power are less in the case when the STATCOM is connected to the Kasoa bus. Similarly as indicated in Table 3, less reactive and active power losses are recorded in the case when the STATCOM is connected to the Kasoa bus

Eigenvalue Analysis

Presented in Table 4 are the results of the Eigenvalue and Eigenvector analyses.

Under the base case scenario, Kasoa bus was detected to be the weakest bus with an eigenvalue of 2.0466. With STATCOM connected to the Kasoa bus, its eigenvalue increased to 7.2246 whiles the eigenvalue of Swedru bus reduced from 5.8508 to 2.5125. On the other hand when the STATCOM was connected at the Swedru bus, eigenvalue of Kasoa bus increased from 2.0466 to 2.2973 and that of the Swedru bus increased from 5.8508 to 6.5809. It can also be said that with the STATCOM installed at the Swedru bus the sensitivity of all the buses increased whiles in the case of installing the STATCOM at the Kasoa bus, the sensitivity of the Swedru bus reduced. Not withstanding the above stated facts, installing the STATCOM at the Kasoa bus is preferable since the weakest bus is of a stability level higher than that of the weakest buses in both the base case and STATCOM installed at Swedru bus.

Participating Factor Analysis

The participation factor for the weakest bus under different system configurations are presented in table 5. Under the base case scenario, Kasoa bus was identified as the weakest bus with a self control of 47.3% and the Swedru bus contributing 37.3%. When the STATCOM was installed at the Swedru bus the Kasoa bus remains the weakest bus with the Swedru bus contributing 36.6% of its voltage. Considering the fact that the Swedru bus voltage under the base case scenario is higher than that of the Kasoa bus, installing a compensator at the Swedru base to bring its voltage to the desired level will surely result in a lower voltage level at the Kasoa bus. This is clearly shown in the load flow result that is when the Swedru bus voltage was forced at 1.02pu the Kasoa bus voltage raised to only 0.9177pu. On the other hand if the STATCOM is installed at the Kasoa bus and its voltage

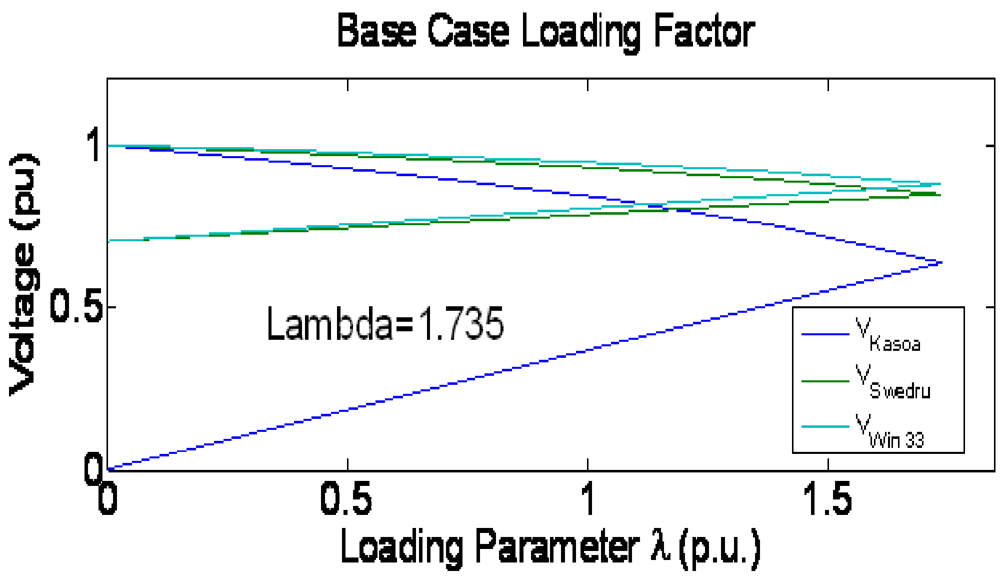

Figure 4 Base Case Loading Factor

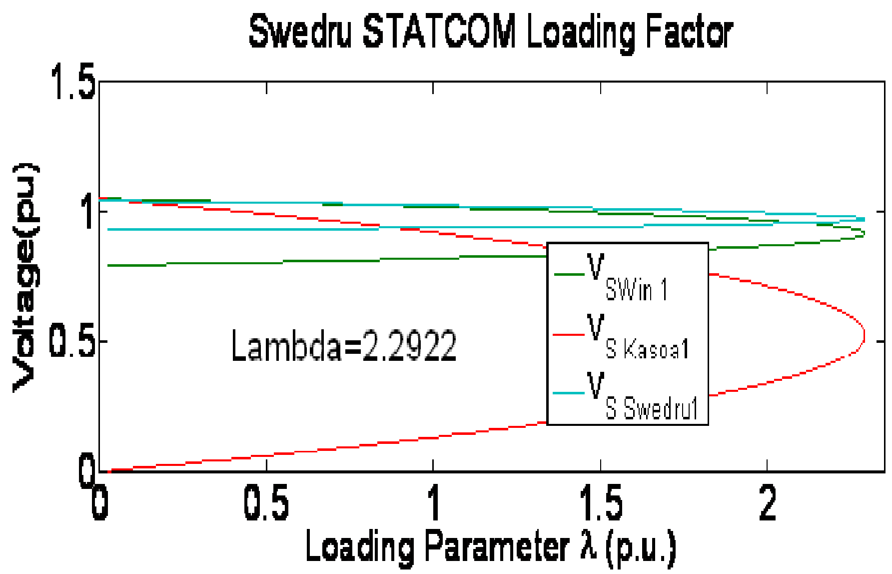

Figure 5 Swedru STATCOM Loading Factor

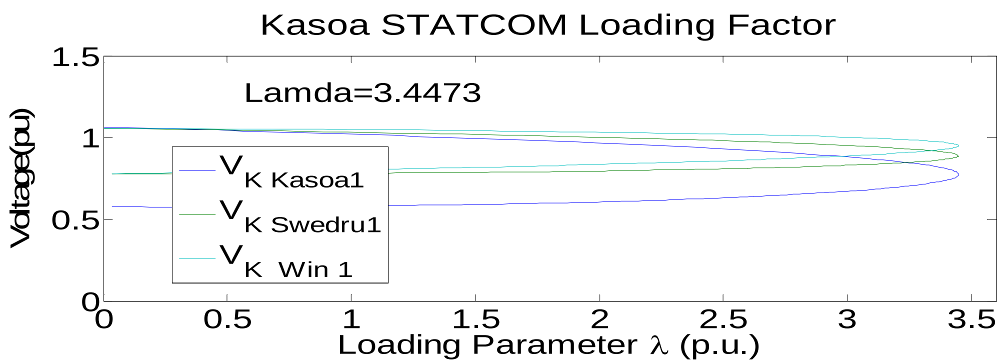

Figure 6 Kasoa STATCOM Loading Factor

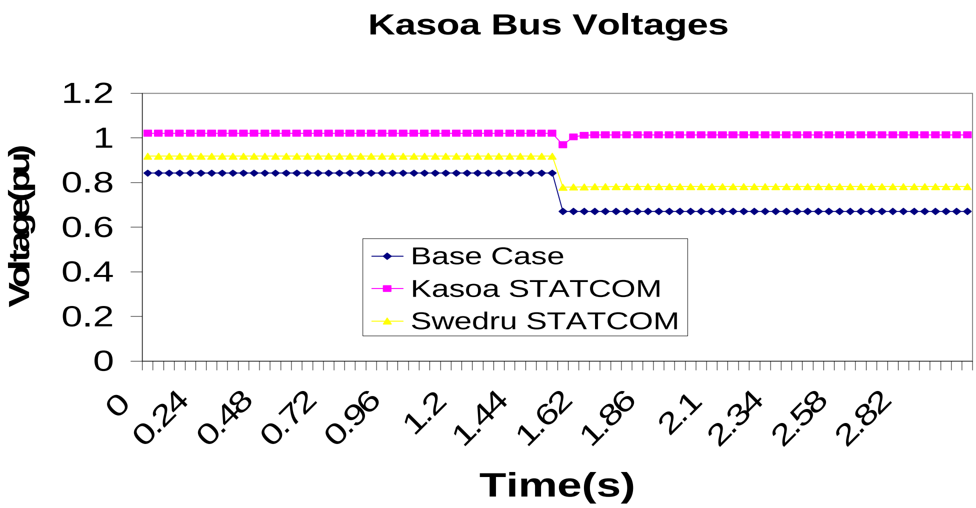

Figure 7 Kasoa Bus Real Time Voltages

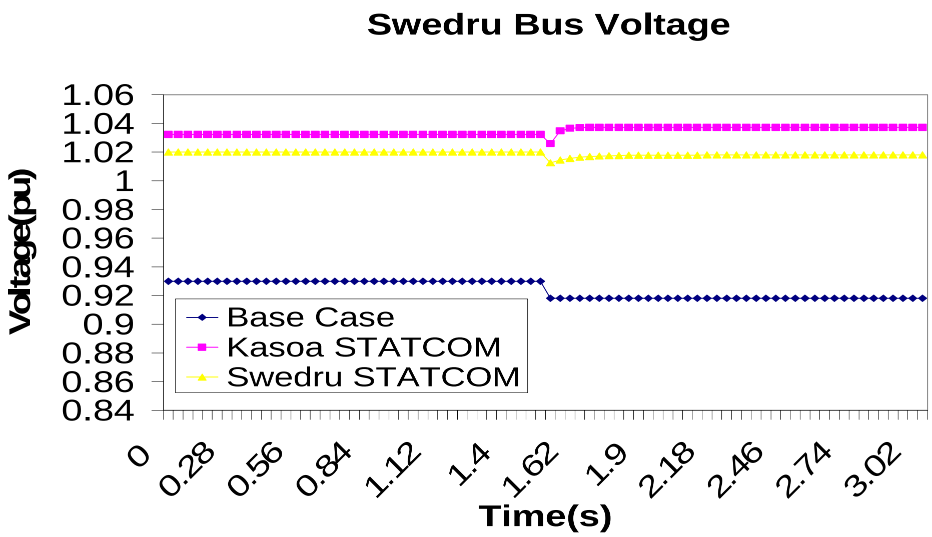

Figure 8 Swedru Bus Real Time Voltages

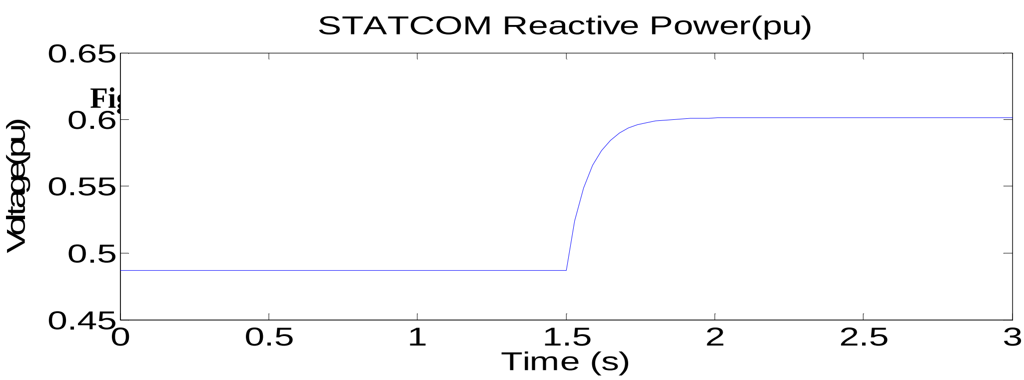

Figure 9 Changes in STATCOM Injected power during contingency

Table 1. Bus Voltage Profile

Bus	V[pu]		
	Base Case	Statcom	
		Kasoa	Swedru
Kasoa	0.8416	1.0200	0.9177
Swedru	0.9298	1.0322	1.0200
Win_161	1.0000	1.0500	1.0500
Win_33	0.9469	1.0475	1.0142

Table 2. Power Generation Summary

	Active	Reactive
Base Case	0.6121	0.4001
Kasoa STATCOM	0.5977	0.3736
Swedru STATCOM	0.603	0.3813

Table 3. Power Losses Summary

Losses	Active	Reactive
Base Case	0.0583	0.0863
Kasoa STATCOM	0.0439	0.0598
Swedru STATCOM	0.0492	0.0675

Table 4. EIGENVALUES OF THE POWER JACOBIAN MATRIX

Most Associated	Base	Kasoa	Swedru
	Real part		
Win_33	26.8028	30.7080	29.0587
Kasoa	2.0466	7.2246	2.29725
Swedru	5.8508	2.5125	6.58086

Table 5. Participation Factor Analysis

Case	Weakest Bus	Participation [%]		
		Kasoa	Swedru	Win_33
Base Case	Kasoa	47.32	37.34	15.33
Kasoa	Swedru	37.71	45.49	16.80
Swedru	Kasoa	47.49	36.59	15.91

Table 6 Results of CPF Analysis

Case	Weakest Bus	At SBN		At 90%
		Voltage	λ	
Base Case	Kasoa	0.4875	1.735	0.6243
Kasoa	Kasoa	0.7663	3.4473	2.771
Swedru	Kasoa	0.5264	2.2922	1.137

pegged at 1.02pu it increased the Swedru bus voltage from 0.9298 to 1.0322pu.

Continuation Power Flow Analysis

Table 6 and figures 4 to 6 indicates the results of the CPF analyses. Installing the STATCOM at the Kasoa bus proved to have the best impart on the systems ability to withstand increase in loading. A loading factor of 3.0964 with a system collapse voltage of 0.7032pu as compared to 0.5264 in the case of STATCOM connected to the Swedru bus. Setting an under voltage protection to operate at the minimum voltage limit of 0.9pu, the system could be loaded up to 2.77pu whiles when the STATCOM is installed at the Swedru bus it can be loaded only up to 1.14pu

Contingency Analysis

A complete contingency analysis could be carried out on only complete meshed network. In the case of radial networks it is obvious that an opening of a breaker or removal of equipment will result in part of the network being isolated. Hence, for the network under study only a line outage was simulated. One out of the two Winneba-Kasoa lines was opened to create a contingency situation. With the STATCOM installed at the Kasoa bus, Swedru bus voltage slightly increased from 1.036 to 1.037pu whiles in the base case scenario the voltage dropped from 0.9298 to 0.9181pu as shown in figure 7. When the STATCOM was installed at the Swedru bus the Kasoa bus voltage dropped from 0.9177 to 0.7817pu and in the base case scenario the voltage dropped from 0.8416 to 0.6702pu as shown in figure 8. It is evident therefore that installing the STATCOM at the Kasoa bus resulted in all the buses having voltages within the accepted limit.

STATCOM Rating

The reactive power demand of the network follows the changes in system parameters that are total load, network parameters and configuration as well as changes in generation. The criterion for sizing STACOM is therefore determined by the partial compensation of reactive power whiles all bus do not violate the accepted voltage limit. From the results obtained as represented in figure 9, the STATCOM

APPENDIX 1				
Test System Parameters				
Table 7 Line Parameters				
Line	Length(km)	R (ohms/km)	X (H/km)	B (F/km)
Win_33-Kasoa -1	30	0.1143	3.00E-04	3.63E-09
Win_33-Kasoa -2	30	0.1143	3.00E-04	3.63E-09
Win_33-Swedru	18	0.1143	3.00E-04	3.63E-09
Transformers Parameters				
Line	Voltage(KV)	R(pu)	X(pu)	Tap Ratio
Win_161-Win_33 -1	161/33	0.0176	0.0627	1
Win_161-Win_33 -2	161/33	0.0176	0.0627	1
Bus Loads				
Bus	Active (pu)	Reactive (pu)		
Swedru	0.0572	0.0324		
Kasoa	0.3831	0.2170		
Slack Bus				
Bus	Voltage(KV)	MVA	Ref Angle(deg)	
Win_161	161	66	0	

injects 0.48704pu under normal system operation condition and injects 0.5888pu reactive power under the studied contingency condition.

For the STATCOM to effectively compensate for reactive power under all conditions it is appropriate to install one of not less than 0.6pu reactive power. Considering the fact that the cost of STATCOM is proportional to its capacity, it is proposed that a fixed capacitor rated 0.4pu is installed alongside a STATCOM rated 0.3pu.

CONCLUSION

This paper presents a proposed technique for selecting a bus for the purpose of installing STATCOM to ensure static voltage instability issue are resolved as well as compensating for reactive power changes during contingencies.

An algorithm comparing analyses based on Eigenvalues and Eigenvectors of load flow Jacobian matrix using Newton-Raphson technique, saddle node bifurcation and contingency analyses are discussed. Also the required STATCOM rating is determined for both normal and contingency conditions by adjusting the STATCOM reactive power settings. A three bus system is used to verify the validity of the proposed algorithm. The Kasoa bus had been identified as the optimum location for connecting a FACTS device for the STATCOM to effectively control voltage under normal and contingency situations without violation of any of the accepted system parameter limits. The obtained result verifies the validity and effectiveness of the proposed algorithm.

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