Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement

Arthit Sode-Yome and N. Mithulananthan
Electric Power System Management, Energy Field of Study, Asian Institute of Technology,
P.O. Box 4, Klongluang, Pathumthani 12120, Thailand
E-mail: mithulan@ait.ac.th

Abstract This paper compares the shunt capacitor, SVC and STATCOM in static voltage stability improvement. Various performance measures are compared under different operating system conditions for the IEEE 14 bus test system. Important issues related to shunt compensation, namely sizing and installation location, for exclusive load margin improvement are addressed. A methodology is also proposed to alleviate voltage control problems due to shunt capacitor compensation during lightly and heavily loaded conditions.

Keywords loading margin; remote voltage control; shunt capacitor; STATCOM; SVC

Modern electric power utilities are facing many challenges due to ever increasing complexity in their operation and structure. In recent years, one problem has that received wide attention is voltage instability.[1–5] The lack of new generation and transmission facilities, and overexploitation of existing facilities together with the increase in load demand make these problems more likely in modern power systems.

Voltage stability is the ability of a power system to maintain adequate voltage magnitude so that when the system nominal load is increased, the actual power transferred to that load will increase.[3,6] The main cause of voltage instability is the inability of the power system to meet the demand for reactive power.[3] Voltage instability is the cause of system voltage collapse, in which the system voltage decays to a level from which it is unable to recover. Voltage collapse may lead to partial or full power interruption in the system.

There are two types of voltage stability based on simulation time; static voltage stability and dynamic voltage stability. Static analysis involves only the solution of algebraic equations[3,7,8] and therefore is computationally less extensive than dynamic analysis. Static voltage stability is ideal for the bulk of studies in which a voltage stability limit for many pre-contingency and post-contingency cases must be determined.

Providing adequate reactive power support at the appropriate location solves voltage instability problems. There are many reactive compensation devices used by the utilities for this purpose, each of which has its own characteristics and limitations.[9] However, the utility would like to achieve this with the most beneficial compensation device. Hence, this paper compares the advantages and disadvantages of the currently available and most commonly used shunt-compensation devices.

Static voltage stability

Static voltage instability is mainly associated with reactive power imbalance. Thus, the loadability of a bus in a system depends on the reactive power support that the bus can receive from the system. As the system approaches the maximum loading point or voltage collapse point, both real and reactive power losses increase rapidly. Therefore, the reactive power supports have to be locally adequate. With static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from a plot of power transferred versus voltage at the receiving end. These plots are popularly referred to as P–V curves or 'Nose' curves. As power transfer increases, the voltage at the receiving end decreases. Eventually, a critical (nose) point, the point at which the system reactive power is out of usage, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, a large voltage drop due to heavy reactive power losses is observed. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse.

Weakest bus

The weakest bus is defined as the bus nearest to experiencing a voltage collapse. If one were to think of this in terms of the received power versus bus voltage (P–V) curve, the weakest bus would be the one that is closest to the turning point or 'Nose' point of the curve. Equivalently, the weakest bus is one that has a large ratio of differential change in voltage to differential change in load (dV/dP_{Total}).[9] Changes in voltage at each bus for a given change in system load is available from the tangent vector, which can be readily obtained from the predictor steps in the continuation power flow process.[4,9] Using reformulated power flow equations, the differential change in the system active power is

$$\mathrm{d}P_{\mathrm{Total}} = C\mathrm{d}\lambda$$

Thus the weakest bus would be

$$Bus = \max\left\{\left|\frac{\mathrm{d}V_1}{C\mathrm{d}\lambda}\right|, \left|\frac{\mathrm{d}V_2}{C\mathrm{d}\lambda}\right|, \dots, \left|\frac{\mathrm{d}V_n}{C\mathrm{d}\lambda}\right|\right\} \tag{1}$$

Since the value of $C\mathrm{d}\lambda$ is the same for each $\mathrm{d}V$ elements in given tangent vector, choosing the weakest bus is as easy as choosing the bus with largest $\mathrm{d}V$ component. In addition to the above method weakest bus could be obtained by looking at the right eigenvectors associated with the smallest eigenvalue as well.[3]

Usually, placing adequate reactive power support at the weakest bus enhances static-voltage stability margins. This can be done with traditional shunt capacitors, or FACTS controllers.[10,11] However, each compensation device has different characteristics, some of them may be problematic as far as the static voltage stability is concern. So, it is important to study their behaviour in order to use them effectively and efficiently.

Shunt capacitor, SVC and STATCOM

It is a well-known fact that shunt compensation can be used to provide reactive power compensation. Traditional shunt capacitors or newly introduced FACTS controllers can be used for this purpose. FACTS controllers are very expensive; Table 1 gives an idea of the cost of various shunt controllers.[12,13] Descriptions of each of these controllers, along with their terminal characteristics, are given in the next subsections.

Shunt capacitor

Shunt capacitors are relatively inexpensive to install and maintain. Installing shunt capacitors in the load area or at the point that they are needed will increase the voltage stability. However, shunt capacitors have the problem of poor voltage regulation and, beyond a certain level of compensation, a stable operating point is unattainable. Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage; during low voltage conditions Var support drops, thus compounding the problem.[7] The characteristic of the shunt capacitor is shown in Fig. 1.

Static Var compensator (SVC)

SVC is a shunt connected static Var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variable.[14,15] Typically, the power system control variable is the terminal bus

TABLE 1 *Cost comparison of shunt controllers*

Shunt controller	Cost (US $)
Shunt capacitor	8/kvar
SVC	40/ kvar (controlled portion)
STATCOM	50/ kvar (controlled portion)

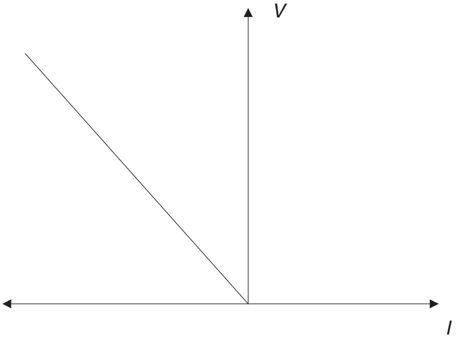

Fig. 1 *Terminal characteristic of shunt capacitor.*

voltage. There are two popular configurations of SVC. One is a fixed capacitor (FC) and thyristor controlled reactor (TCR) configuration and the other one is a thyristor switched capacitor (TSC) and TCR configuration.

In the limit of minimum or maximum susceptance, SVC behaves like a fixed capacitor or an inductor. Choosing appropriate size is one of the important issues in SVC applications in voltage stability enhancement. Figures 2 and 3 show the basic structure and terminal characteristic of a SVC, respectively.

Static synchronous compensator (STATCOM)

STATCOM is a voltage-source converter based device, which converts a DC input voltage into an AC output voltage in order to compensate the active and reactive needs of the system.[15] STATCOM has better characteristics than SVC; when the system voltage drops sufficiently to force the STATCOM output to its ceiling, its maximum reactive power output will not be affected by the voltage magnitude. Therefore, it exhibits constant current characteristics when the voltage is low under

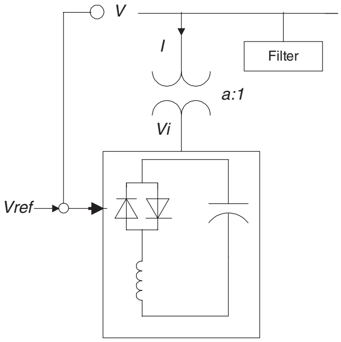

Fig. 2 *Basic structure of SVC.*

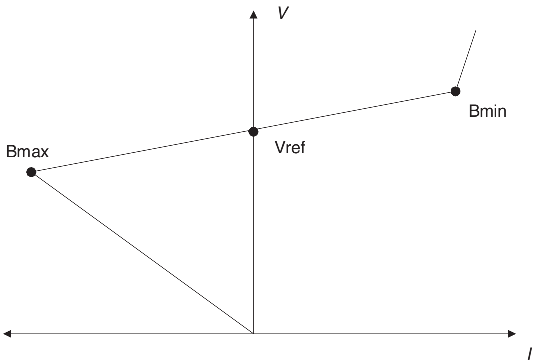

Fig. 3 *Terminal characteristic of SVC.*

the limit. A schematic diagram and STATCOM characteristic are shown in Figs. 4 and 5, respectively.

Test system and analytical tools

A single line diagram of the IEEE 14 bus test system[16] is depicted in Fig. 6. It consists of five synchronous machines, including three synchronous compensators used only for reactive power support. There are twenty branches and fourteen buses with eleven loads totaling 259 MW and 81.4 MVar.

All the results presented in the paper were produced with the help of the UWPFLOW, power system analytical tool.[17] UWPLOW is a research tool that has been designed to calculate the maximum loading margin of a power system associated with a saddle node and limit-induced bifurcation for a given load and genera-

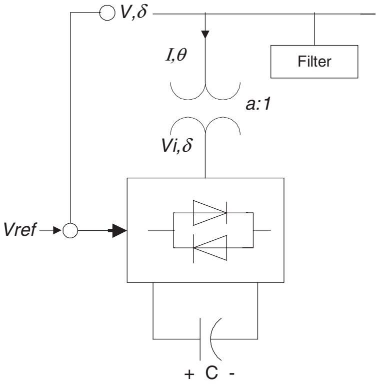

Fig. 4 *Basic structure of STATCOM.*

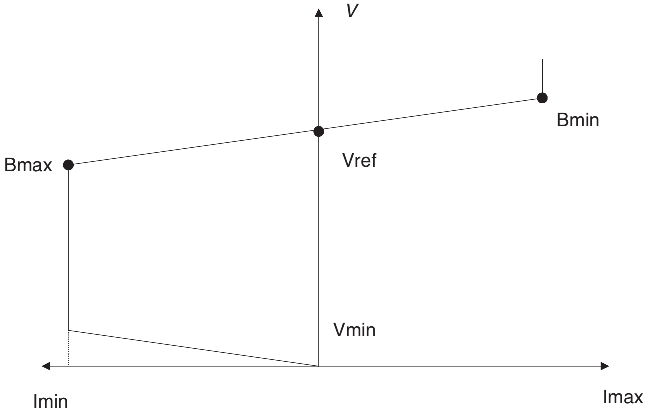

Fig. 5 *Terminal characteristic of STATCOM.*

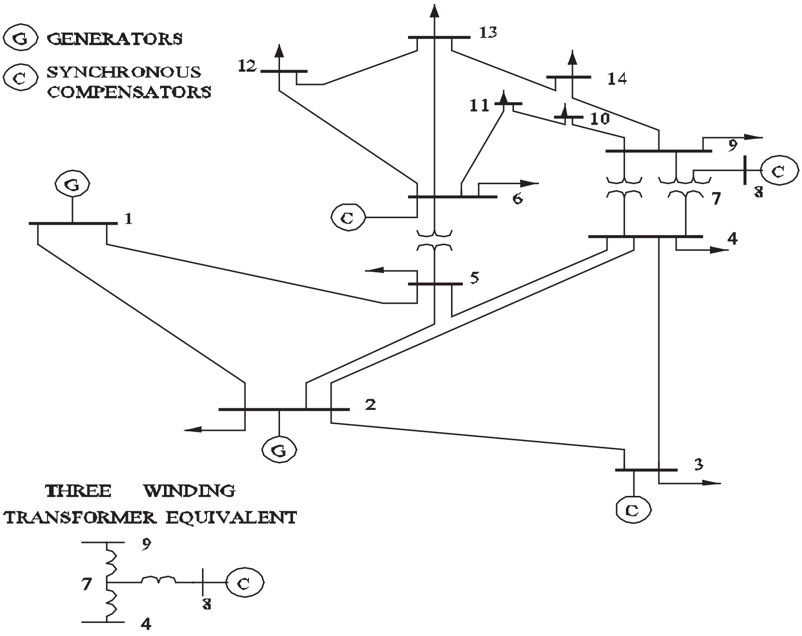

Fig. 6 *Single line diagram of IEEE 14 bus test system.*

tion ‘direction’. The program has detailed static models of various power system elements such as generators, loads, HVDC links, and various FACTS controllers, particularly SVC and STACOM controllers in phase and PWM control schemes, representing control limits with accuracy for all models.

In this study, in order to obtain P–V curves and hence the loading margin of the system for different cases, all loads were represented as constant *PQ* and increased simultaneously according to equation (2), i.e. maintaining constant power factor.

$$\begin{aligned} P_L &= P_o(1+\lambda) \\ Q_L &= Q_o(1+\lambda) \end{aligned} \tag{2}$$

where P_o and Q_o correspond to the base loading conditions and λ is the loading factor (LF).

Results and discussion

The best location for reactive power compensation as far as the improvement of static voltage stability margin is concerned, is the ‘weakest bus’ of the system. The weakest bus of the system can be identified using tangent vector analysis, as explained in the previous section. Table 2 shows the first four weakest buses. Table 2 indicates that bus 14 could be considered the best location for a reactive power support.

TABLE 2 *Tangent vector of the first four weakest buses*

Bus No.	|Tangent Vectors|
14	0.14617
13	0.13520
10 and 12	0.13167

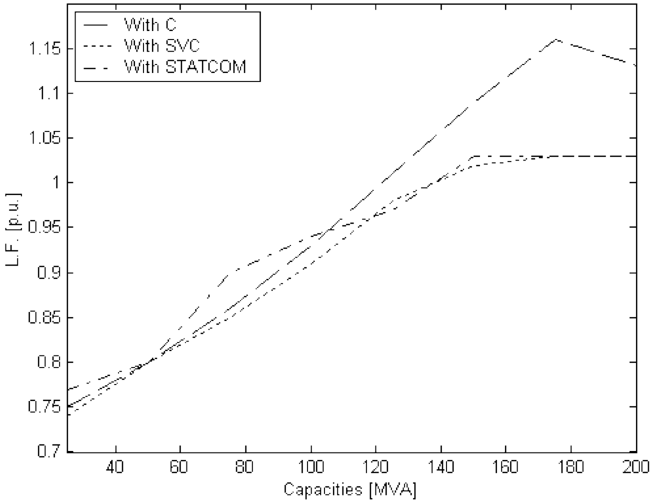

Fig. 7 *Loading margin versus controller capacities for shunt controllers.*

Rated capacities of shunt capacitor, SVC and STATCOM

In order to get a rough estimate of reactive power support needed at the weakest bus and the corresponding load margin for a given load and generation direction, a synchronous compensator with no limit on reactive power was used at the weakest bus. The amount of reactive power generated at the maximum loading point from the synchronous compensator was found to be 150 MVar. This is a good starting point for different controller capacities.

Another method of determining the capacities is to find the relationship between the maximum loading factor (LF) and the corresponding capacities that the devices can deliver without causing voltage collapse. The loading factor is the factor by which real and reactive power loads are increased to calculate the maximum loading point, according to equation (2). These relationships for the shunt capacitor, SVC and STATCOM are given in Fig. 7.

It is clear from Fig. 7 that the optimum capacity required for both SVC and STATCOM is 150 MVar, the same as the value obtained from the synchronous compensator study. Beyond this capacity there is no improvement in loading margin. However, shunt capacitors can give higher values of LF since they only deliver reactive power without controlling the voltage magnitude at any bus. Notice that the system loading margin with shunt capacitor decreases after reaching a maximum value.

As two methods give the capacity ±150 MVar, it will be used as the maximum reactive power capacity for SVC and STATCOM. For the shunt capacitor, due to the unrealistic voltage profile outside the acceptable range 0.95–1.05 p.u., only a moderate value of 100 MVA is used. In this case, the reactive power supplied changes according to the voltage magnitude at the position the capacitor is connected.

PV curves and voltage profiles

PV curves at the weakest bus of the base case, with various shunt compensation devices, are given in Fig. 8. In the base case, the voltage drops dramatically to an unacceptable value beyond a LF of 0.4 p.u. and collapses at LF = 0.7 p.u. As can be seen from the P–V curves, all the devices improve the static voltage stability margin of the system; however, the voltage level of the weakest bus with shunt capacitor at the lightly loaded condition is unacceptably high. For SVC and STACOM, the voltage profile is within the acceptable range, even at high loading as expected. Voltage profiles with capacitor at 150 MVA were unacceptably high at the lightly loaded condition and very low at the heavily loaded condition. A snapshot of the voltage profile at all buses with different controllers is given in Fig. 9 at LF = 0. Notice that with the shunt capacitor, many of the buses experience a high voltage whereas with SVC or STATCOM all buses remain within the acceptable voltage range.

Shunt capacitors can be used to increase the voltage stability of the system by moving the nose point of PV curve out and up. However, due to the very rapid drop in voltage near the nose point, the best warning signal of a gradual decline in system

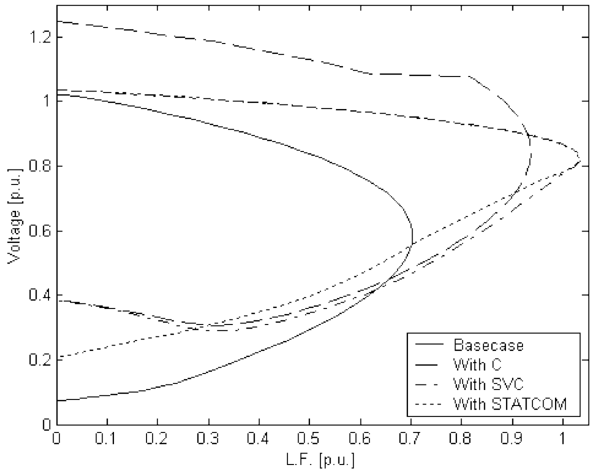

Fig. 8 *PV curves of base case, with various shunt controllers.*

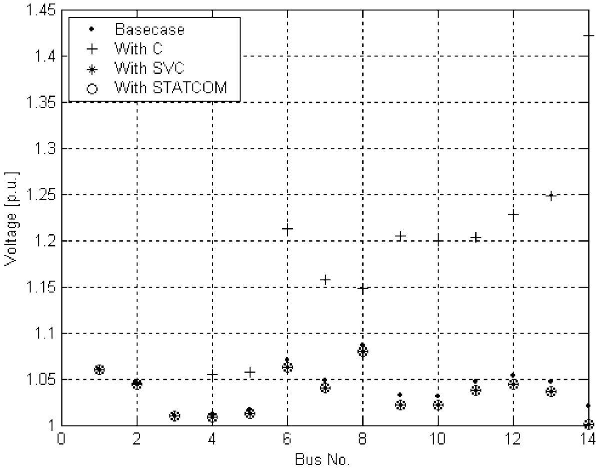

Fig. 9 *Voltage profiles of each bus at zero LF for different controllers.*

voltage is last. A shunt capacitor cannot be connected gradually because there is no warning to the system operator about the coming collapse point. Using SVC and STATCOM gives a warning voltage decline before reaching the collapse point. SVC and STATCOM significantly affect the shape of the PV curve, improving the critical point without masking the nose point by only an outward shift of the PV curve. The use of a shunt capacitor may lead to an unacceptable voltage magnitude in normal operation, and the amount of reactive power delivered is mostly dependent on the voltage magnitude. Hence, it may increase the power transfer capability but will not improve voltage stability, compared to SVC and STATCOM.

The SVC and STATCOM can do a much better job, improving voltage stability while keeping the voltage magnitude in the acceptable region. When the maximum limit is reached, the SVC behaves exactly like a fixed shunt capacitor, so close attention has to be given to selecting the correct size. This is clearly depicted in Fig. 10. The same argument can be extended to STATCOM.

As can clearly be seen from Figs 10 and 11, for both SVC and STATCOM beyond 150 MVar size the voltage decline is smooth and there is no improvement in load system loading margin.

Power losses in the system

To explore the benefits and drawbacks of these controllers, real and reactive power losses in the system at various loading levels were calculated and compared for the different controllers under study.

Active and reactive power losses in the system at different loading points with different controllers are given in Figs 12 and 13, respectively. Real and reactive power losses appear to follow the same pattern in this test system. Notice that at higher loading factors, both real and reactive power losses increase very rapidly. System losses increase with the inclusion of a capacitor at the lightly loaded condi-

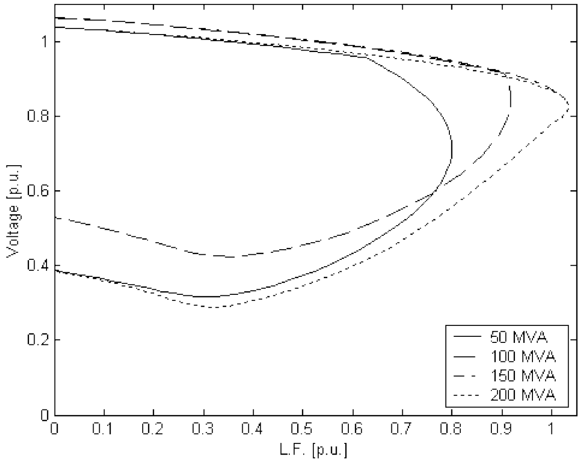

Fig. 10 *PV curves at the weakest bus with different SVC capacities.*

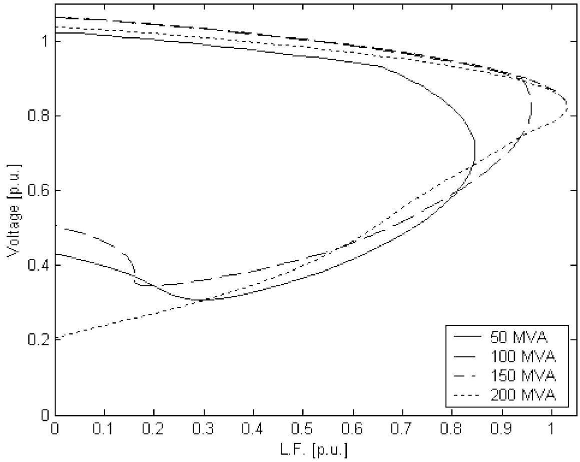

Fig. 11 *PV curves at the weakest bus with different STATCOM capacities.*

tion. Losses with a capacitor included were even higher at a capacity of 150 MVA, especially under lightly loaded conditions, due to the unacceptable voltage profile. There is no significant improvement in loss reduction with SVC or STATCOM under lightly loaded conditions up to LF = 0.2 p.u. However, a substantial reduction in losses is achieved under high load conditions.

Power transfer capability of heavily loaded lines

Figure 14 shows power flows in some lines at LF = 0. Notice that all controllers increase the power flow or power transfer capability of those transmission lines,

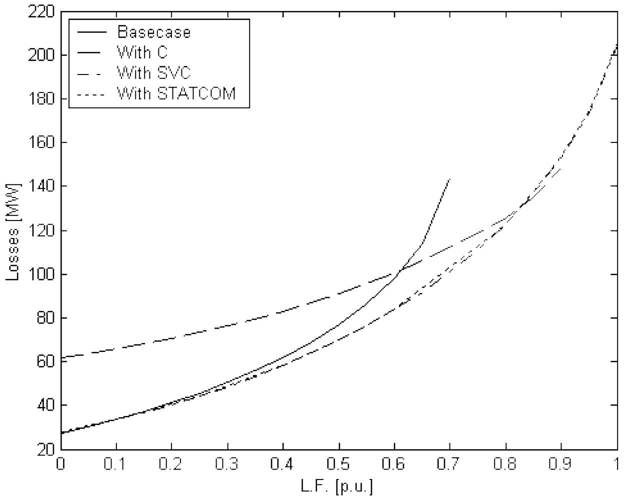

Fig. 12 *Active power losses in system for different shunt controllers.*

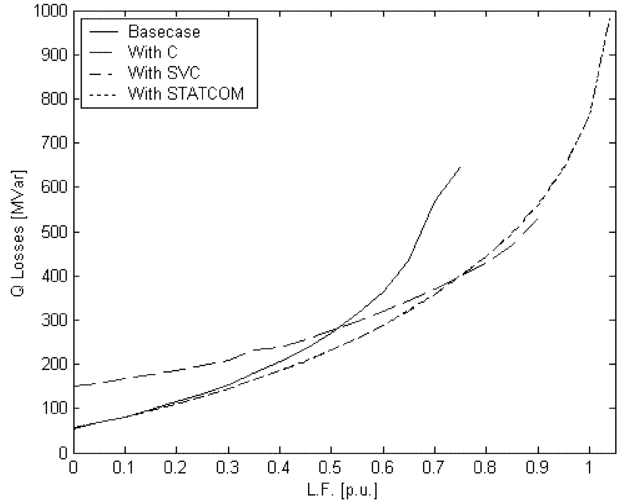

Fig. 13 *Reactive power losses in system for different shunt controllers.*

however, SVC and STACOM perform better by allowing more power than the other two cases.

System loading margin with line outages

In the case of contingencies, system characteristics change. The first three most severe contingencies of the system are found by determining the load flow solution

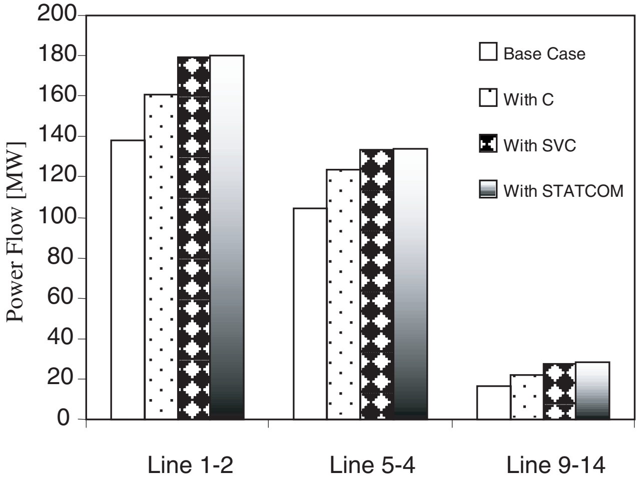

Fig. 14 *Power flow in lines 1–2, 5–4 and 9–14.*

TABLE 3 *Loading margins for various line outages for the base Case, and with different shunt controllers*

	Loading margins (p.u.) for line outages		
Case	1–2	2–3	1–5
Base case	No solution	0.25664	0.34077
C	0.16985	0.44536	0.55317
SVC	0.08505	0.37807	0.58865
STATCOM	0.08357	0.37664	0.58652

at maximum LF, i.e. the heavy loaded line at the collapse point. The outages of line 1–2, 2–3 and 1–5 are the first three severe cases in the system. The system behaves like a radial system since there are only two generators located at bus 1 and 2. The lines adjacent to the generators have to carry the heaviest load and tend to have the most severe outages. The maximum loading margin for each outage is given in Table 3 for different cases.

Table 3 shows that the most severe contingency in the system is the outage of line 1–2, which makes the base case unstable. However, with a shunt capacitor, SVC or STATCOM, the system has a small load margin for the line 1–2 outage case. Also notice that the shunt capacitor performs better in the first two line outage cases, providing the maximum loading margin in each case. This is because the SVC and STATCOM try to maintain the voltage at the connecting bus (Bus 14) at the reference value.

After the contingency, the weakest bus in the system is now not bus 14 since system conditions have changed. Since the capacitors at bus 14 only deliver reactive power without controlling the voltage at any bus, it increases the voltage magnitude throughout the system. Although it improves voltage stability, it offers an unacceptable voltage level. However, introducing some capacitors distributed across bus 2 or 3 (weak buses) is possible, whereas it is not practical to use SVC or STATCOM because of the high cost.

The LFs in the case of line 2–3 outage are close in all controllers. The LF for SVC and STATCOM is higher than that for C in the case of line 1–5 outages. SVC and STACOM can help the system, since the drop in voltage of line 1–5 and line 2–3 is smaller than that in line 1–2.

Remote voltage control

The voltage magnitudes in the system with a shunt capacitor, especially under lightly loaded conditions, are unacceptable. This is due to the fact that the voltage at the capacitor node is not regulated and is very high. This problem can be solved by introducing a remote voltage control scheme at the bus where the capacitor is connected with the help of a neighbouring generator. In this study, it was found that a shunt capacitor combined with remote voltage control could increase the load margin to the maximum in all cases, while keeping the voltage at the weakest bus to an acceptable value. Table 4 shows the load margin of the system with capacitor and remote voltage control.

Conclusions

A comparison study of the shunt capacitor, SVC and STATCOM used for static voltage stability margin enhancement is presented. Various merits and demerits of the shunt compensation devices are discussed in detail. The importance of selecting an adequate size SVC and STATCOM is also discussed; this is an important issue as far as voltage stability is concerned, as these devices suffer voltage control problems at the limits.

The shunt capacitor, SVC and STATCOM increase the static voltage stability margin and power transfer capability, however, SVC and STACOM provide better behaviour in terms of loss reduction and voltage profile. The increase in losses with a shunt capacitor under lightly loaded conditions is due to the poor voltage profile. A remote voltage control scheme can be implemented to solve the voltage control problem at the shunt capacitor bus.

Overall, SVC and STACOM behave better than a simple shunt capacitor, however, these controllers are expensive when compared to the shunt capacitor. A complete

TABLE 4 *Loading margin with C only and with C and remote voltage control*

	LF (p.u.)	Remarks
Capacitor	1.16	Poor voltage profile overall
Capacitor and remote voltage control	1.42	Good voltage profile overall

cost–benefit analysis has to be carried out to justify the economic viability of the SVC and STACOM.

References

1 N. Mithulananthan and S. C. Srivastava, 'Investigation of a voltage collapse incident in Sri Lankan power system network', International Conference on Energy Management and Power Delivery '98 (EMPD'98, Singapore), pp. 47–53 (1998).

2 P. Didsayabutra, N. Mithulananthan and B. Eua-aroporn, 'Static voltage stability study on Thailand power system network', 12th International Conference on the Electric Power Supply Industry, 12th CEPSI, Pattaya, Thailand, No. 34-31 (1998).

3 IEEE/PES Power System Stability Subcommittee, 'Voltage stability assessment: concepts, practices and tools,' Special Publication, Final document (2002).

4 C. A. Cañizares and F. L. Alvarado, point of collapse and continuation methods for large AC/DC systems, *IEEE Trans. Power Syst.*, **8**(1) (1993), pp. 1–8.

5 A. C. Zambroni de Souza, 'Discussion on some voltage collapse indices', *Electr. Power Syst. Res.*, **53**(1), (2000), 53–58.

6 KEMA-ECC, '*Interconnected Power System Dynamics Tutorial*' (EPRI, 1998).

7 P. Kundur, *Power System Stability and Control*, EPRI Power System Engineering Series (McGraw-Hill, New York, 1994).

8 K. P. Kessel and H. Glavitsch, 'Estimating the voltage stability of power system', *IEEE Trans. Power Deliv.*, **PWRD-1** (1986), 346–351.

9 V. Ajjarapu and C. Christy, 'The continuation power flow: a tool for steady state voltage stability analysis,' *IEEE Trans. Power Syst.*, **7** (1992), 416–423.

10 A. R. Messina, M. A. Perez and E. Hernandez, 'Coordinated application of FACTS devices to enhance steady-state voltage stability', *Electr. Power Energy Syst.*, **25**(4) (2003), 259–267.

11 J. Douglas, 'FACTS: the delivery system of the future', *EPRI J.*, **17**(7) (1992), 4–11.

12 GE, 'Guide for economic evaluation of flexible AC transmission systems (FACTS) in open access environment,' technical report, EPRI-TR 108500. Final report prepared by GE, New York, 1997.

13 J. V. Coevering, J. P. Stovall, R. L. Hauth, P. J. Tatto, B. D. Railing and B. K. Johnson, 'The next generation of HVDC- needed R&D, equipment costs, and cost comparisons,' *Proc. EPRI Conference of Future of Power Delivery*, Washington DC, 1996.

14 D. Thukaram and A. Lomi, 'Selection of static VAR compensator location and size for system voltage stability improvement', *Electr. Power Syst. Res.*, **54**(2) (2000), 139–150.

15 N. Mithulananthan, C. A. Cañizares and J. Reeve, 'Comparison of PSS, SVC and STATCOM controllers for damping power system oscillation', *IEEE Trans. Power Syst.*, **18** (2003), 786–792.

16 N. Mithulananthan, C. A. Cañizares and J. Reeve, 'Indices to detect Hopf bifurcations in power systems', *NAPS-2000*, Waterloo, ON, 2000.

17 C. A. Cañizares *et al.*, 'UWPFLOW: continuation and direct methods to locate fold bifurcations in AC/DC/FACTS power systems,' University of Waterloo, available at http://www.power.uwaterloo.ca (1998).