CHAPTER 4

VOLTAGE SUPPORT BY DISTRIBUTED STATIC VAR SYSTEMS (SVS)

4.1 Introduction

In this chapter it is shown that when load centers require Static VAR Systems (SVS) for regulated voltage control, the strategy of using many, small, distributed SVS located at distribution buses is more advantageous than a few large bulk SVS located at the transmission or sub-transmission bus. The advantages are: (i) standby to meet N-1 reliability criterion is reduced; (ii) costly high voltage transformers are no longer needed because the SVS can be connected directly to the low voltage distribution buses; (iii) distribution-side voltage support is more effective because the total MVAr requirement of the distributed SVS is less. Simulation studies have demonstrated that the distributed SVS units operate harmoniously together.

Faced with the difficulty of securing rights-of-way for new transmission lines, increasing reliance is placed on Static VAR Systems (SVS) to provide voltage support to the increasingly overloaded existing lines. In this chapter the term SVS is treated as a continuously controllable source of reactive current. It represents a combination of switched capacitors, switched inductance (for economy) and thyristor SVCs or STATCOMs (to give continuously adjustable control between the capacitor steps).

Presently, large bulk SVSs are located at the transmission or sub-transmission buses. This raises the specter of voltage collapse should the SVS fail. N-1 reliability criterion requires a redundant set of SVS. This chapter presents a preliminary evaluation of the alternative of using many small SVSs located at the low voltage distribution buses. With distributed SVSs, when any one of the M units fails, there are still M-1 units remaining to provide voltage support. Apart from satisfying the reliability criterion better, distributed SVS bring other savings as well.

Historically, synchronous condensers, connected at the sub-transmission and transmission buses, have been used to supply the continuously adjustable capacitive or inductive currents to support the voltages at the load centers. Because of the precedence set by synchronous condensers, the SVS which have largely supplanted them, still tend to be situated at the sub-transmission and transmission buses. With the availability of STATCOMs or SVCs (cheaper) which can be connected at distribution level voltages without the need of transformers [47,48,68], it is timely to examine whether regulated voltage support should be by:

(1) a single or a few bulk SVSs connected at the transmission or sub-transmission buses.

or

(2) many small-sized distributed SVSs units connected at distribution buses.

This chapter presents the reasoning and some preliminary quantitative evaluations which support the case for distributed SVS. The objective is to arrive at positive interim conclusions which justify further in-depth studies further. The conceptual design of a substation serving a load center is given at the end of the chapter. Lastly, simulations have been used to show that many SVS units do not interact adversely to cause instability.

4.2 Model of Transmission Line to Load Center

A number of assumptions befitting a preliminary study have been used. Per-unit base referred to the transmission voltage side is used in the study and resistive losses are neglected.

In order to highlight the mechanism of "voltage drop" and conversely "voltage support", the radial transmission line is represented by an inductive reactance jX between the sending-end voltage $\mathbf{V_S}$ and receiving-end voltage $\mathbf{V_R}$ as illustrated in Fig. 25. The "telegraph line equations" could have been used, but the purpose of this chapter is to highlight the "mechanism" of voltage support using simple phasor diagrams. In presenting a Conceptual Design in Section 4.8, the "telegraph line equations" will be used to predict the inductive and the capacitive MVArs required to prevent overvoltage and undervoltage when loading below and above the Surge Impedance Level (SIL), respectively. For the present, the formula of the transmission reactance for different line length is $X=0.0013\, l$ p.u. of the surge impedance, where l is the length in km. M equal loads taking load currents $\mathbf{I_L}$/M each is supplied from the bus of $\mathbf{V_R}$. Transformers, whose leakage reactances are jMX_T, bridge the high transmission line voltage $\mathbf{V_R}$ to low the distribution voltage $\mathbf{V_L}$ of the loads. The transformer reactance is assumed to be X_T=0.10 p.u. The distributed SVS supply current $\mathbf{I_{Cd}}$/M directly at the load buses without transformers because the distribution voltage is within the capability of existing SVS technology.

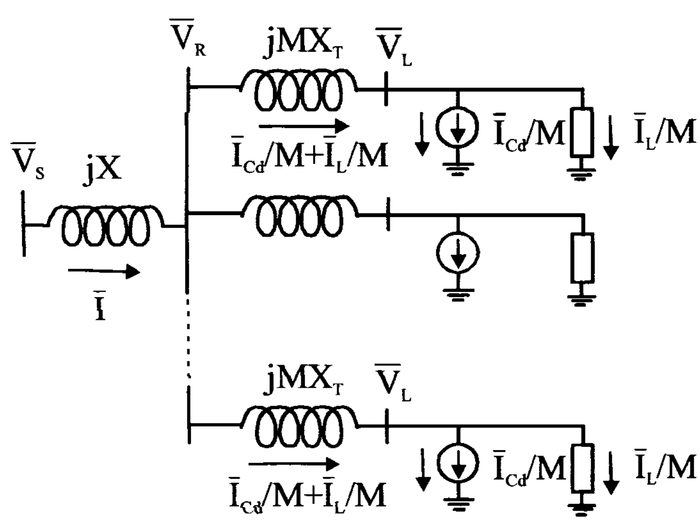
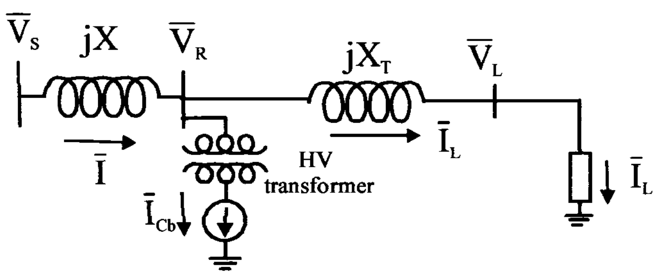
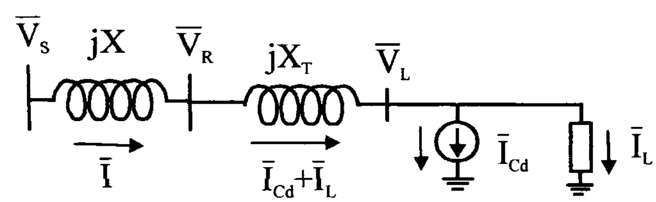


Figure 25 Single line diagram of transmission line (jX) between $\mathbf{V_S}$ and $\mathbf{V_R}$. M transformers (jMX_T) connect transmission line to M loads. Distribution SVS currents $\mathbf{I_{Cd}}$/M provide voltage support of load voltage $\mathbf{V_L}$.

The M transformers and the loads of Fig. 25 have been replaced by single transformer of reactance jX_T and a single load current $\mathbf{I_L}$ in Fig. 26. Fig. 26 a) and b), respectively, show the bulk SVS compensation current $\mathbf{I_{Cb}}$ at the transmission voltage bus side and the distributed SVS compensation current $\mathbf{I_{Cd}}$ at the distribution voltage bus side. Fig. 26 a) includes an additional transformer which is required to raise the voltage output of the SVS to the transmission line voltage of $\mathbf{V_R}$.



(a)



(b)

Figure 26 Single line diagram with M loads of Fig.1 equivalenced as a single load carrying current $\mathbf{I_L}$. (a) Bulk SVS connected to bus of $\mathbf{V_R}$ by additional transformer; (b) Distributed SVS located at bus of $\mathbf{V_L}$.

4.3 Case For Distributed SVS

The findings of this preliminary study point to potential cost savings arising from: (i) reduction of standby MVAr needed to satisfy N-1 reliability criterion; (ii) reduced MVAr rating in the distributed SVS of Fig. 26 b); (iii) not needing the high voltage transformer of Fig.26 a).

4.3.1 Reliability

The loss of the bulk SVS in Fig. 26 a) affects the entire load center. N-1 reliability criterion requires there must be K units, K=2,3,4,..,, on standby and each unit has to be rated at the 1/(K-1) times the full MVAr required. The total cost is expressed as K/(K-1) times the full MVAr required.

In the system of Fig. 26 b), there are already M sets of distributed SVSs. It is a matter of rating each SVS at 1/(M-1) times the full MVAr required.

4.3.2 Effectiveness of Compensation

The "mechanism" of voltage control is complex and the details are outlined in the analysis in Section 4.4. However the basic idea is simple: as viewed from the load, an inductive current $\mathbf{I} = -jI_i$ flowing across transmission line inductive reactance jX produces a voltage drop of $-XI_i$ and a capacitive current $\mathbf{I} = jI_C$ produces a voltage boost of $+XI_c$. In Fig. 26 a), the bulk SVS current $\mathbf{I}_{Cb}$ passes through the transmission line reactance jX only. In Fig. 26 b) the capacitive current $\mathbf{I}_{Cd}$ passes through a larger reactance $j(X+X_T)$ since the load transformer reactance jX_T is added in the capacitive current path. Because of the larger reactance $j(X+X_T)$, the compensation produces a higher voltage boost/drop in Fig.26 b) than in Fig. 26 a). This simple-minded picture has been used as a guide only. Rigorous circuit theory analysis in Section 4.4 is applied to compare the MVAr requirements of Fig. 26 a) and Fig.26 b).

4.3.3 Potential Cost Saving of High Voltage Transformer

The bulk SVS in Fig. 26 a) requires a transformer to raise its output to transmission voltages. Additional transformers are not required in Fig.26 b) because the distributed SVS can be connected directly, without transformers, to the low voltage distribution buses. Therefore, there is a potential saving in cost.

4.4 Voltage Regulation Analysis

Voltage support analysis has mostly been approached at the quadratic level of complex power S=P+jQ. As will be shown below, the linear circuit theory approach using complex phasors of voltages and currents is more insightful.

The base line used in the comparative studies is that the load is a unity power factor load, i.e the load current $\mathbf{I_L}$ is in phase with the voltage of the load bus $\mathbf{V_L}$. As is well known, lagging power factor load depresses the load bus voltage further. The VARs required to correct the poor power factor will be accounted separately from the VARs required for voltage support of unity power factor loads. This is in line with the approach taken in the classic reference. Following this approach, the objective is to derive the formulae of the MVAr required for voltage support exclusively.

4.4.1 Bulk VAr Compensation at High Voltage Bus of V_R

The phasor diagram of Fig. 27 is for the study of voltage regulation by bulk SVS located at the bus of $\mathbf{V_R}$ in Fig. 26 a). When the bulk SVS regulates the receiving-end voltage $\mathbf{V_R}$ at 1.0 p.u. voltage, V_L the magnitude of the load voltage $\mathbf{V_L}$ must be less than 1.0 p.u. (The per unitization is based on the voltage-base of the transmission line side.) The voltage drop is due to the voltage across the transformer reactance jX_T.

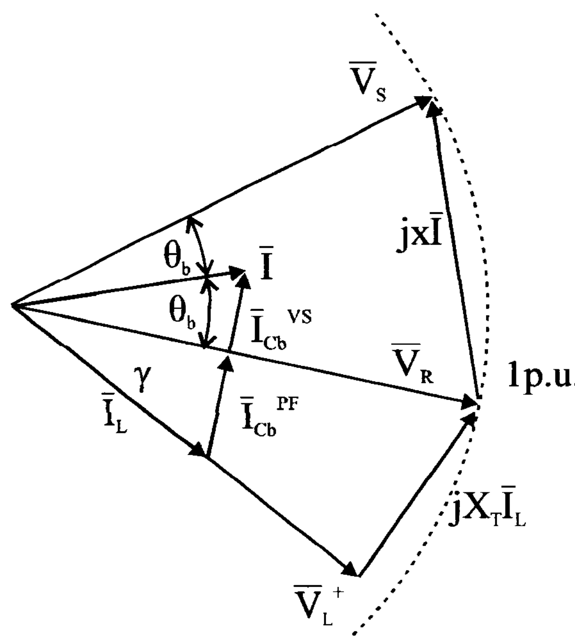


Figure 27 Phasor diagram--system of Fig. 26 a), Bulk SVS at Transmission Bus.

4.4.1.1.Phasor Diagram of Load Transformer

Fig. 27 shows $\mathbf{V_L}$ and $\mathbf{I_L}$ in phase for unity power factor operation, i.e. $P=V_L\ I_L$. It is necessary to compute the load voltage magnitude V_L for any load power P. For $|\mathbf{V_R}|=1.0$, applying Pythagoras Theorem to the right angle triangle formed by $\mathbf{V_R}$, $\mathbf{V_L}$ and $jX_T\mathbf{I_L}$

$$\left(X_T I_L\right)^2 + \left(V_L\right)^2 = 1 \tag{4.1}$$

Substituting $I_L=P/V_L$, (4.1) yields a quadratic equation of $(V_L)^2$. Solving the equation and choosing the solution which is nearest to 1.0 gives,

$$\left|\overline{V}_L\right| = \sqrt{\frac{1+\sqrt{1-4\left(X_L P\right)^2}}{2}} \tag{4.2}$$

The value of V_L^+ is defined as the solution of (4.2) for P=1.0. V_L^+ will be kept for the analysis of distributed SVS below. Although V_L^+ is less than 1.0 p.u., by choosing the transformer turns ratio, the distribution bus voltage can be 35 kV or 25 kV of the standard. The angle opposite to $jX_T\mathbf{I_L}$ is γ. From the properties of right angle triangle,

$$\gamma = \arccos(V_L^+) \tag{4.3}$$

4.4.1.2 Phasor Diagram of Transmission Line

In the triangle formed by $\mathbf{V_S}$ and $\mathbf{V_R}$ enclosing the angle $2\theta_b$, the power equation is

$$P = \frac{|\bar{V}_S||\bar{V}_R|}{X}\sin 2\theta_b \tag{4.4}$$

For V_S=V_R=1.0

$$\theta_b = \frac{1}{2}\arcsin(PX) \tag{4.5}$$

The transmission line current **I** is perpendicular to **jXI** and bisects the angle $2\theta_b$. The current of the bulk SVS is:

$$\bar{I}_{Cb} = \bar{I} - \bar{I}_L \tag{4.6}$$

$\mathbf{I_{Cb}}$ lies along the constant power line so that

$$|\bar{I}|\cos\theta_b = |\bar{I}_L|\cos\gamma \tag{4.7}$$

$\mathbf{I_{Cb}}$ consists of two parts: $\mathbf{I_{Cb}^{VS}}$ for transmission line compensation (voltage support) and $\mathbf{I_{Cb}^{PF}}$ for transformer compensation (power factor correction). The SVS current decomposed into the two components is

$$\left|\bar{I}_{Cb}\right| = \left|\bar{I}\right| \sin\theta_b + \left|\bar{I}_L\right| \sin\gamma \tag{4.8}$$

Dividing (4.8) either the LHS or RHS of (4.7) and multiplying throughout by P, it can be shown that the reactive power of the bulk SVS is

$$Q_b = P\left(\tan\theta_b + \tan\gamma\right) \tag{4.9}$$

In (4.9), P tan θ_b is for compensating the reactance jX of the transmission line and P tan γ is for the reactance jX_T of the transformers.

4.4.1.3 MVA Requirements of Transformers

In addition to the M load transformers, the bulk SVS requires a transformer to step up its low voltage to high transmission line voltage.

4.4.1.3.1 MVA Rating Requirement of Load Transformers

The high voltage side of the load transformers must be rated at $|\mathbf{V_R}|$=1.0 p.u. The current requirement is $I_L=1/V_L^+$. The MVA requirement of all the M load transformers is $|\mathbf{S_{b\,Load}}| = 1/V_L^+$, for V_L^+ taken from (4.2) for the case P=1.0.

4.4.1.3.2 MVA Rating Requirement of Transmission Bus SVS Transformer

The MVA rating of the high voltage transformer must be $|\mathbf{S_{bSVS}}|$=P ($\tan\theta_2+\tan\gamma$) for γ given by (4.3) and θ_b given by (4.5).

4.4.2 Distributed VAR Compensation at bus of V_L

Fig. 28 is the phasor diagram of Distributed SVS compensation. In order that the comparison is on the same foot, the load voltage is regulated at $|\mathbf{V_L}| = |\mathbf{V_L}^+|$ and the load power P is delivered at unity power factor. The closing side of the voltage triangle formed by $\mathbf{V_S}$ and $\mathbf{V_L}^+$ is $j(X+X_T)\mathbf{I}$. $\mathbf{I}$ lies perpendicular to $j(X+X_T)\mathbf{I}$ and makes an angle θ_d with $\mathbf{V_L}^+$. The angle δ lies between and $\mathbf{V_S}$ and $\mathbf{V_L}^+$.

The real power P is

$$P = \frac{\left|\overline{V}_L^+\right|\left|\overline{V}_S\right|}{X + X_T}\sin\delta \tag{4.10}$$

For V_S=1,

$$\delta = \arcsin\left(\frac{P(X + X_T)}{\left|\overline{V}_L^+\right|}\right) \tag{4.11}$$

The angle, which $\mathbf{I}$ makes with $\mathbf{V_L}$, is θ_d. The angle, which $\mathbf{I}$ makes with $\mathbf{V_S}$, is $(\delta-\theta_d)$. The power transmitted at $\mathbf{V_S}$ is $P=|\mathbf{I}|\cos(\delta-\theta_d)$. The power received at $\mathbf{V_L}^+$ is $P=|\mathbf{V_L}^+||\mathbf{I}|\cos\theta_d$. Equating the two powers,

$$\cos(\delta - \theta_d) = \left|\overline{V}_L^+\right|\cos\theta_d \tag{4.12}$$

Substituting the trigonometry identity $\cos(\delta-\theta_d)=\cos\delta\cos\theta_d + \sin\delta\sin\theta_d$ in (4.12), it can be shown that

$$\theta_d = \arctan\frac{\left|\overline{V}_L^+\right| - \cos\delta}{\sin\delta} \tag{4.13}$$

The current of the distributed SVS is

$$\bar{I}_{Cd} = \bar{I} - \bar{I}_L \tag{4.14}$$

This current vector lies on the constant power line so that

$$|\bar{I}|\cos\theta_d = |\bar{I}_L| \tag{4.15}$$

The magnitude of the SVS current is

$$|\bar{I}_{Cd}| = |\bar{I}|\sin\theta_d \tag{4.16}$$

The reactive power of the distribution SVS is

$$Q_d = P\tan\theta_d \tag{4.17}$$

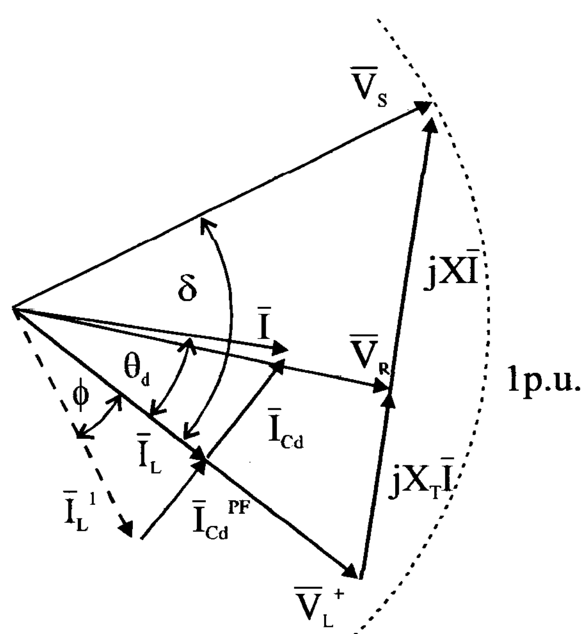


Figure 28 Phasor diagram—system of Fig.26 b), Distributed SVS at load bus.

4.4.2.1 Load with Lagging Power Factor

Normally the load current lags $\mathbf{V_L}$ by a power angle ϕ. Fig. 28 illustrates this case by the broken line phasor of the load current $\mathbf{I_L}^1$. When the load receives the same real power P, $\mathbf{I_L}^1$ must lie along the same constant power locus so that

$$\left|\bar{I}_L^1\right|\cos\phi = \left|\bar{I}_L\right| \tag{4.18}$$

Therefore in order to correct the lagging power load, the distributed SVS should take another capacitive current component $\mathbf{I_{Cd}}^{PF}$ whose magnitude is $I_L^1\sin\phi$ and whose direction is the same as $\mathbf{I_{Cd}}$. In this case $\mathbf{I} = \mathbf{I_L}^1 + \mathbf{I_{Cd}} + \mathbf{I_{Cd}}^{PF}$. The total current of the VAR compensator is $\mathbf{I_C} = \mathbf{I_{Cd}} + \mathbf{I_{Cd}}^{PF}$.

The VAR required for power factor compensation is

$$Q_d^{PF} = P\tan\phi \tag{4.19}$$

Since the load can have different power factors, the systematic approach is to consider that Q_d^{PF} is for power factor correction. For the remainder of this chapter, the focus is placed on $Q_d = P \tan \theta_d$, the requirement for voltage support.

4.4.2.2 MVA Rating Requirement of Load Transformers

The voltage rating of the load transformers must be V_L^+ p.u. The load current is $I_L=1/ V_L^+$. From (4.15) the magnitude of the transformer current **I** is $I= I_L /\cos \theta_d$. Therefore the MVA requirement of the load transformers is $|\mathbf{S_{d\ Load}}| = V_L^+ I = 1/ \cos \theta_d$.

4.5. Comparison of MVAr Requirement of SVS

For comparisons to be meaningful, the same real powers, P=1p.u., are drawn from the load bus at unity power factor and the load voltage $|\mathbf{V_L}| = V_L^+$. For distributed SVS the MVAr is calculated from $Q_d = P \tan\theta_d$, where θ_d is computed from (4.13). For bulk SVS at the transmission line voltage $\mathbf{V_R}$, $Q_b = P(\tan\theta_b + \tan\gamma)$ where θ_b and γ are taken from (4.5) and (4.3) respectively. $P\tan\gamma$ compensates jX_T of the load transformers and resembles an overhead requirement irrespective of transmission line length. $P\tan\theta_b$ compensates the line reactance jX and since X=0.0013 x km it increases with the length of the transmission line.

Fig.29 presents Q_d and Q_b in per-unitized MVAr plotted against the line length in km. The savings Q_b-Q_d, in adopting distributed SVS in preference over bulk SVS, varies from 5% to 10%, depending on the length of the transmission line. The 10% corresponds to X_T, the transformer leakage reactance.

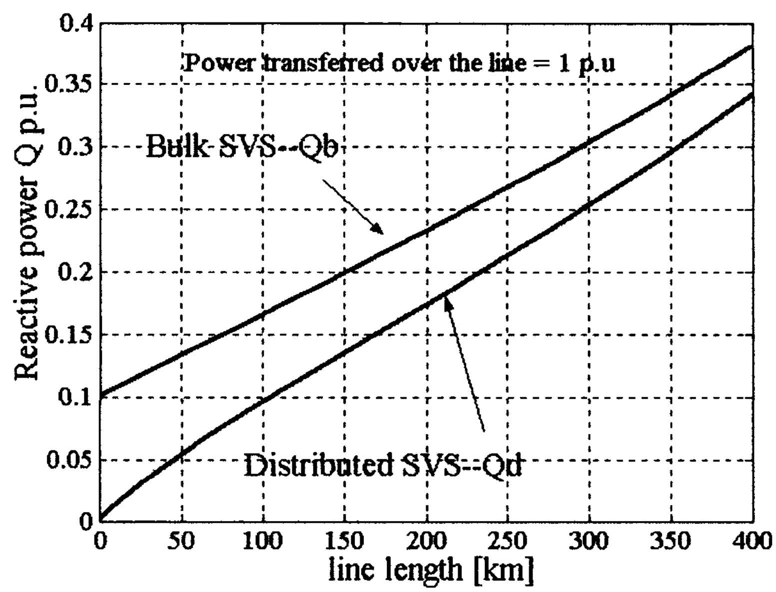


Figure 29 MVAr (p.u.) requirement of SVS plotted against transmission distance (km). Bulk SVS--Q_b ; Distributed SVS--Q_d. ($X=0.0013\ l$ km, X_T=0.10 p.u.)

4.6 Comparison of MVA Requirements of Transformers

For real power, P=1, for distributed SVS, the MVA rating of all the M load transformers is $|S_{d\ Load}| = 1/\cos\theta_d$, where θ_d is computed from (4.13). For bulk SVS, the MVA rating of all the M load transformers is $|S_{b\ Load}| = 1/V_L^+$ with V_L^+ computed from (4.2). The additional transformer to step up the voltage of the bulk SVS to transmission line voltage must have an MVA rating of : $|S_{b\ SVS}| = (\tan\theta_b + \tan\gamma)$ where θ_b and γ are taken from (4.5) and (4.3) respectively.

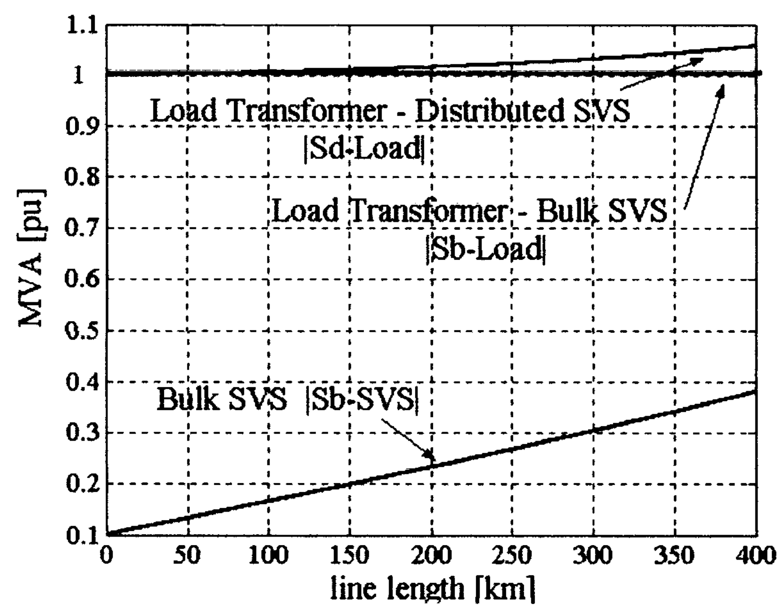


Figure 30 MVA (p.u.) of transformers plotted against transmission distance (km). $|S_{b\ SVS}|$ ---transformer connecting Bulk SVS to power system. Load Transformers: $|S_{b\text{-}Load}|$ --Bulk SVS; $|S_{d\text{-}Load}|$ --Distributed SVS. (X=0.0013 l km, X_T=0.10 p.u.)

Fig. 30 presents the per-unitized MVA of load transformers: $|S_{d\ Load}|$ of distributed SVS and $|S_{b\ Load}|$ of bulk SVS plotted against the line length. Bulk SVS requires its own transformer of $|S_{b\ SVS}|$ rating. In using distribution SVS, the compensating currents pass through the load transformers so that their MVA have to increase especially when transmission line is long.

4.7 Discussion

4.7.1 Cost of VAR Compensators - Bulk Size vs. Distribution Size

The savings, Q_b-Q_d, in MVARs shown in Fig. 29 translate to lower costs in the Static VAR Compensators or STATCOM and switched capacitors for distributed SVS. However there is a cost component related to controls. Since every unit has its own controls, this cost component of distributed SVS increases with M, the number of units.

4.7.1.1 Estimate in Savings

As it is difficult to obtain cost of equipment from manufacturers, the authors have presented in Table I, the estimates of savings based on the MVAR of *SVS* saved multiplied to $/kVAR of SVC or STATCOM which have been listed in [69,70]. The MVAr saved is based on a conservative estimate of 5% (taken from Fig.29). Cost estimates for STATCOM and SVC are: STATCOM 50$/kVAr and SVC 40$/kVAr. Although the references were dated in 1996, the numbers provide reasonable guidance in 2004.

4.7.2 Cost of Transformers

In <u>distributed SVS</u>, there is a potential saving because the high voltage transformer of the bulk SVS of Fig. 26 a) is not required. However, the compensating currents from the distributed SVS of Fig. 26 b) must still pass through the M load transformers. Therefore their total MVA rating must be increased as $|S_{d\ Load}|$ shows in Fig.30. As the voltage rating is kept regulated at V_L+, it is the current rating which is increased thus requiring thicker copper windings.

Bulk SVS requires an additional transformer with MVA rating of $|\mathbf{S_{b\,SVS}}| = (\tan\theta_2 + \tan\gamma)$. As the transformer carries Q_b of the bulk SVS, the plot of $|\mathbf{S_{b\,SVS}}|$ in Fig.30 is the same as Q_d in Fig.29. Not having to pay for a high voltage transformer of this MVA rating is an important saving knowing that it can make up to 20% of overall cost of SVC [69,70]. However, this has to be compared with the increase in the MVA of load transformers of distributed SVS. Since reactive power is added vectorially to the real power of the load, i.e. $|\mathbf{S_{d\,Load}}| = [1+Q_d^2]^{0.5}$, the increase only by about 7% for 400 km in Fig.30.

Table I

Savings from reduced Mvar of SVS

Nominal Voltage l-l [kV]V_{BASE}	230 [kV]	345 [kV]	500 [kV]	735 [kV]
$P_{SIL} = S_{BASE}$ [MVA]	140	420	1000	2280
savings [pu]	0.05	0.05	0.05	0.05
savings [MVAr]	7	21	50	114
savings [$] voltage support provided entirely by STATCOM	350000	$1.05 million	$2.5 million	$5.7 million
savings [$] voltage support provided entirely by SVC	280000	840000	$2 million	$4.56 million

4.7.3 Cost of AC Circuit Breakers

Each SVS has its AC Circuit Breaker. The cost of M Circuit Breakers at distribution voltage level and each having MVA rating at $PM/(M-1)\cos\theta_1$ is to be compared with the cost of K Circuit Breakers of bulk SVS each rated at $PK(\tan\theta_2 + \tan\gamma)/(K-1)$ MVA rating at transmission or sub-transmission voltage level.

4.7.4 Cost of Redundancy

In bulk SVS of Fig. 26 b), N-1 reliability criterion requires K SVS for standby. Expressed in terms of MVAr, the cost of redundancy is $KQ_b/(K-1)$

In distributed SVS, the cost is $MQ_d/(M-1)$.

4.7.5 General Note

It should be noted that V_L^+ is defined and required for this work only. It fulfils the function of ensuring that the bulk SVS and distributed SVS are evaluated on equal footing. In other studies of distributed SVS where comparisons are not needed, the load bus voltage will be set as V_L=1.0 p.u. This will simplify Fig. 28 as $\mathbf{V_L}$ will lie on the unit circle and $\delta=2\theta_d$.

4.8 Conceptual Design of Power Delivery Substation

This section presents the conceptual design example of a 315/25 kV substation receiving power in the range of 50 MW to 375 MW from a 300 km long, 315 kV line. The desired voltage profile in the line is: at the sending end $|\mathbf{V_S}|$=315 kV and at the receiving end at the 25 kV busses of the substation, the load voltage is regulated at $|\mathbf{V_L}|$=25kV. The substation load is assumed to be at 90 percent power factor. The SVS units are located on the 25 kV bus of the substation.

4.8.1 MVAR Requirements of Substation

In the preceding sections, for simplicity in presenting the comparative merits of the transmission voltage vs. distribution voltage locations of the SVS, the lossless lumped inductance has been used to model the transmission line. Unfortunately, such a model cannot predict overvoltages when the load is below the Surge-Impedance Loading (SIL). In this section, the distributed parameter model is used. As the method is familiar to most readers, it is necessary only to recall that the single-conductor line is characterized by:

z, impedance per km (z = 0.474 ohm/km, from [71])

y, admittance per km (y = 3.33x10^{-6} S/km, from [71])

$Z = z{\cdot}l$ and $Y = y{\cdot}l$, where l is the length of the line in km. $Z_S = \sqrt{z/y} = 377\ ohms$, $\mathbf{V_S}$ is 315 kV hence the Surge-Impedance Loading (SIL) of the line (= | $\mathbf{V_S}$ |^2/Z_S) is 250 MW.

At the receiving end, it can be shown that the real and reactive powers are given by:

$$P = \frac{|V_S||V_R|}{B}\sin\delta \tag{4.20}$$

$$Q_R = -\frac{|V_R|^2 A}{B} + \frac{|V_S||V_R|}{B}\cos\delta \tag{4.21}$$

where | $\mathbf{V_S}$ | is the sending-end voltage, | $\mathbf{V_R}$ | is the receiving-end voltage, δ is the angle between | $\mathbf{V_S}$ | and | $\mathbf{V_R}$ |, $A = \cosh\sqrt{ZY}$ and $B = Z\frac{\sinh\sqrt{ZY}}{\sqrt{ZY}}$.

$$l\sqrt{zy} = 1.256x10^{-3}(300) = 0.377 radians = 21.6^\circ$$

$$A = \cosh\sqrt{ZY} = \cosh l\sqrt{zy} = \cos 21.6^\circ = 0.9298$$

$$B = Z\frac{\sinh\sqrt{ZY}}{\sqrt{ZY}} = zl\frac{\sinh l\sqrt{zy}}{l\sqrt{zy}} = 0.474x300\frac{\sin 21.6^\circ}{0.377} = 138.85$$

Integrating the transmission line equations with the step-down transformer leakage reactance, the Q_R required by the transmission line, to meet the voltage constraint $|V_S|$=315 kV and $|V_L|$=25kV at both ends of the line, is shown in Fig. 31 under the label "Line". Inductive MVARs are required to counter overvoltage for light loads and capacitive MVARs for heavy loads. The cross-over takes place at the Surge Impedance Loading (SIL) of 250 MW.

Before proceeding further, a brief digression is in order. In Section 4.3, mention has been made that the transformer reactance jX_T contributes to the effectiveness of voltage support when the SVS is on the 25 kV side. This has been demonstrated by the quantitative comparison appearing in Fig.29 by which the capacitive MVARs of Distributed SVS is less than that of Bulk SVS. This raises the question as to whether the transformer reactance jX_T can contribute to reducing the -50 MVAR (inductive) required to prevent overvoltage when operating under low load condition. In transmitting 375 MW at 0.9 pf, the MVA base is 375/0.9=416.6 MVA. For 25 kV, it can be shown that the Z_{base} phase is 0.50 ohm. Assuming that –50 MVAR is provided by jX_{SVC} the inductive reactance of SVCs, the equivalent value of X_{SVC} =4.16 or 8.32 pu. The transformer reactance is taken as X_T=0.1 pu. Therefore, the size of X_{SVC} can be reduced to (8.32-0.1=) 8.22 pu. As this reduction is small, it is neglected for the remainder of this chapter.

There is a second requirement for capacitive MVARs. This is for unity power factor correction of the loads. For load operating at 0.9 pf, Q_{pf} the capacitive MVARs required is shown in Fig.31 under the label "Load". The total MVARs required at the substation is $Q_T=Q_R+Q_{pf}$ is shown under the label "Operating range of the SVS". In this chapter the term "SVS" covers a combination of switched inductor, switched capacitors and power electronic VAR controllers such as SVSs or STATCOMs.

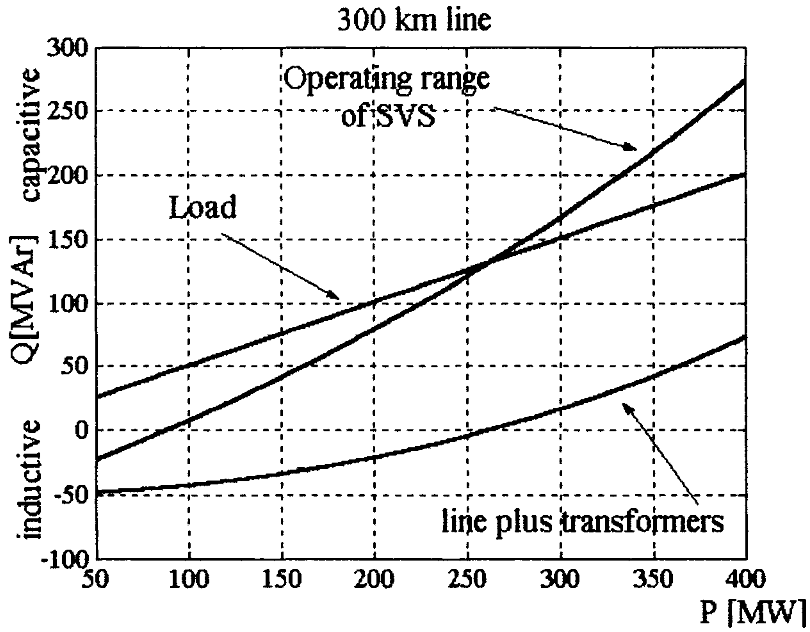


Figure 31 Operating range of SVS. (requirement for load from 50MW to 375 MW)

4.8.2 Substation

As shown in Fig. 32, the conceptual design of the substation consists of: high-voltage line terminations, high-voltage busbars, power transformers, low-voltage busbars and low-voltage line terminations. Breaker-and-a-half is used for both voltage levels main-buses in order to fulfill the reliability of power supply. Three 125 MW power transformers are chosen for the total power of 375 MW. One spare transformer is also used to increase the reliability. The total power distribution at 25 kV level is divided by 4 buses, each is around 125 MW. Each bus has one SVS with five terminations of 25 MW each. The SVS, located on the 25 kV bus of the substation, control the reactive power (unity power factor) so as to regulate the bus voltage at 25 kV.

4.8.3 Rating of Transformers

The 181 MVAR capacitive required for power factor correction does not cross the transformers. Thus the transformers must be rated to carry the maximum real power of 375 MW and the capacitive reactive power Q_R =60 MVAR (according to Fig. 31), which is required to support the receiving end voltage of the transmission line from dropping. The total MVA of the transformers should be $(375^2+60^2)^{0.5}$=379 MVA. In choosing 3 transformers, the MVA required for each is 127 MVA. For (N-1) reliability, 4 transformers, each rated at 125 MVA, are chosen in the substation layout as illustrated in Fig.32.

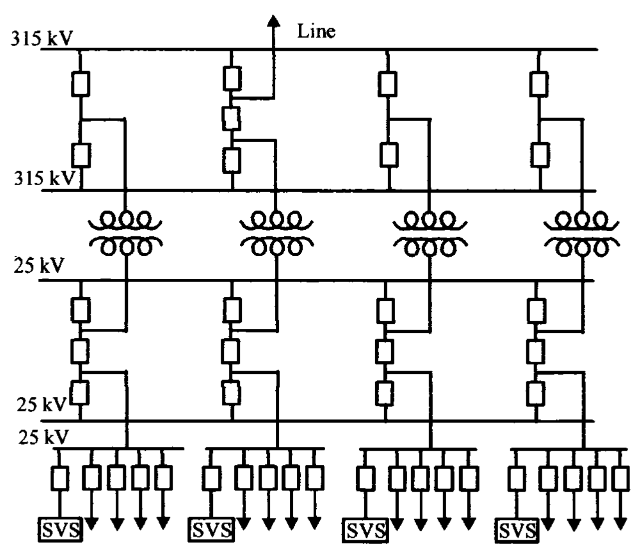


Figure 32 Single Line Diagram for 315/25 kV, 375 MW substation

4.8.4 Rating of SVS

From Fig. 31, the total MVAR requirement of the SVS ranges from -50 MVAR (inductive) to 240 MVAR (capacitive) (60 MVAR for voltage support +180 MVAR for pf correction). For (N-1) reliability, the requirements for each of the four SVS are: -16.7 (=-50/3) MVAR (inductive) and 80 (=240/3) MVAR (capacitive). As there is one SVS for each of the four 25 KV busses, failure of any one SVS leaves a total of -50 MVAR (inductive) to 240 MVAR (capacitive), so that N-1 reliability is satisfied. The SVS can be realized by the Static VAR Compensator (SVS) using thyristor technology or the STATCOM using GTO or IGBT technology.

4.8.4.1 Rating of SVC

For the realization by SVCs as illustrated by Fig. 33, each of the four 25 kV busses will have: one SVC with inductive VAR= 20 MVAR

4 sets of Switched Capacitors rated at 20 MVAR each

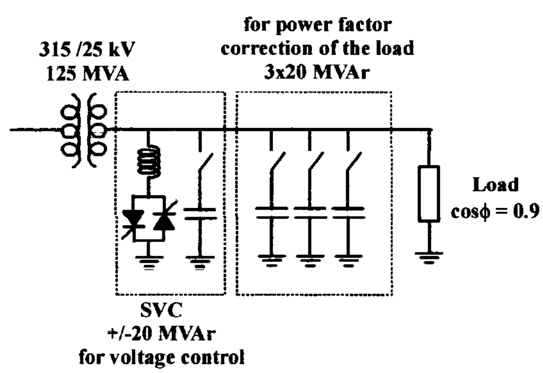


Figure 33 Single Line Diagram of SVS realized with SVC for voltage control and switched capacitors for power factor correction of the load

4.8.4.2 STATCOM

For the realization by STATCOMs as illustrated by Fig. 34, each of the four 25 kV busses will have: one STATCOM rated at ±20 MVAR

3 sets of Switched Capacitors rated at 20 MVAR each.

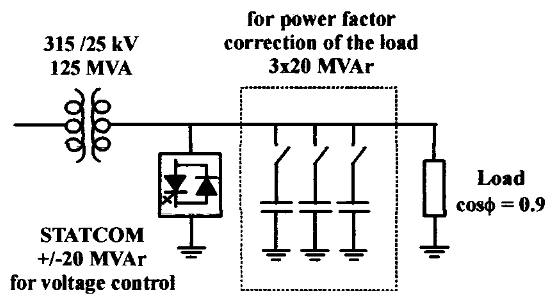


Figure 34 Single Line Diagram of SVS realized with STATCOM for voltage control and switched capacitors for power factor correction of the load

4.9 Dynamic Performance

As the preceding analysis is meaningless if the distributed SVSs will interact adversely against each other during transients, simulations studies have been performed which should put to rest such concern. The simulations have been carried out using HYPERSIM [72], a real-time simulator based on parallel computers developed by Hydro-Quebec. The value of HYPERSIM in comes from the availability of default models of transformers, induction motors and transmission lines (distributed line inductance and capacitance) based on many years experience of Hydro-Quebec researchers. All models are very accurate of high order. The real-time capability of HYPERSIM is not important in the simulations carried out.

The system which has been simulated consists of system from Fig. 32 which is connected to an infinite bus by a 300 km long 315 kV line. The power transferred over the line is 375 MW. Half of the load is resistive. The other half is induction motor driving constant torque load (compressor load of air-conditioning and refrigeration). The SVS is based on STATCOMs. Each STATCOM has its own control circuit. Only local feedback is used. Fig. 35 shows the case of the sudden loss of STATCOM #2 in the system of Fig. 32. The simulated instantaneous voltages at each ac bus have been converted to RMS voltages and displayed in Fig. 35 a) against the reference voltages. The waveforms show that the transients disappear within 0.05s and the maximum voltage deviation is only about 0.1 kV (0.7% of rated 25 kV). Fig. 35 b) records the simulated instantaneous phase currents of the STATCOMS which lead the phase voltages by 90^0. The sudden loss of STATCOM #2 is apparent in the disappearance of the current. The other three STATCOMs respond by increasing their currents to make up for the lost one. The simulation clearly shows that any fear that instability arising from the STATCOMs interacting adversely with each other is groundless.

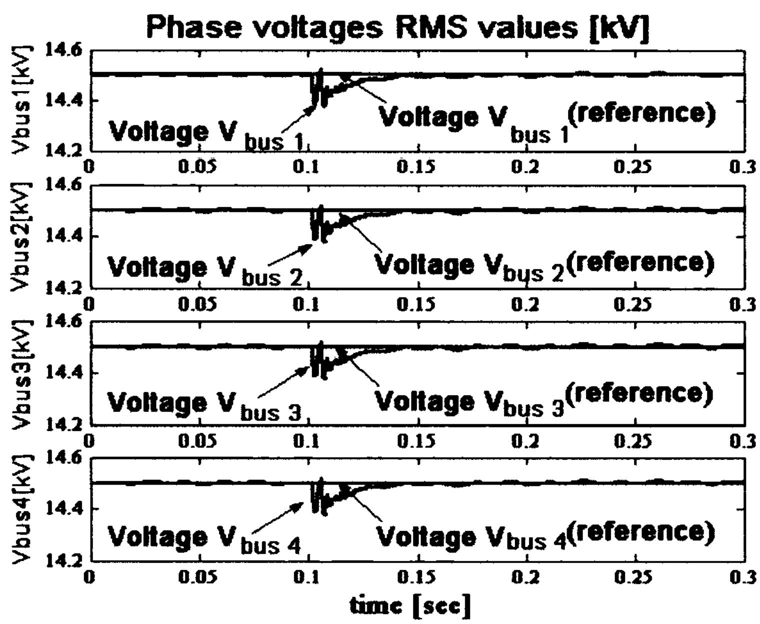


Figure 35 a) Phase voltages of 25 kV bus of Fig.32 when STATCOM #2 is lost

Fig. 36 shows the case of the sudden disconnection of one load bus as happens when its circuit breaker trips. Fig. 36 a) shows RMS values of phase voltages of supported buses. Fig. 36 b) shows phase-a current of every STATCOM. The lowest trace on Fig 36 b) shows power transferred over the transmission line. Once again, the results demonstrate that the STATCOMS operate harmoniously.

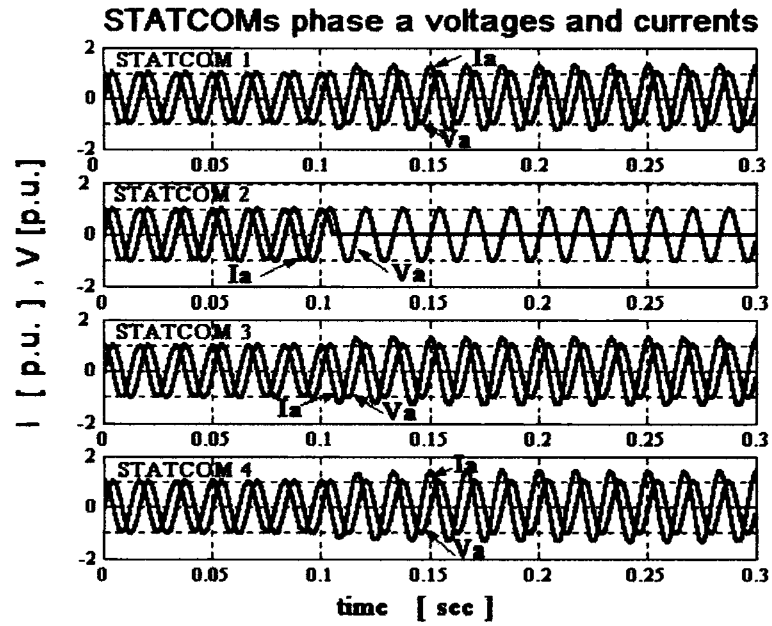


Figure 35 b) Voltages and current of one phase of every STATCOM of Fig.32. Current disappears when STATCOM #2 is lost (Q_{base} = 25 MVAr)

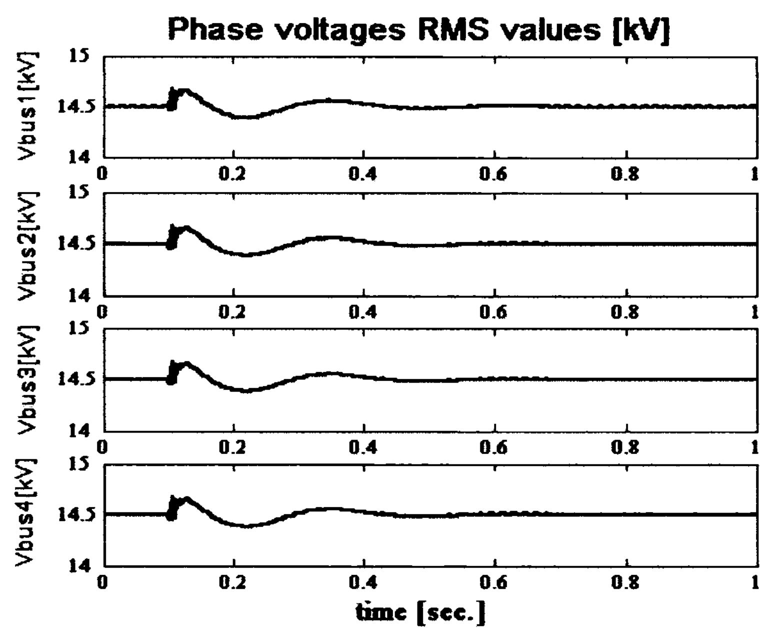


Figure 36 a) Phase voltages (rms) of 25 kV bus of Fig.32 when circuit breaker trips thus disconnecting load and STATCOM #2.

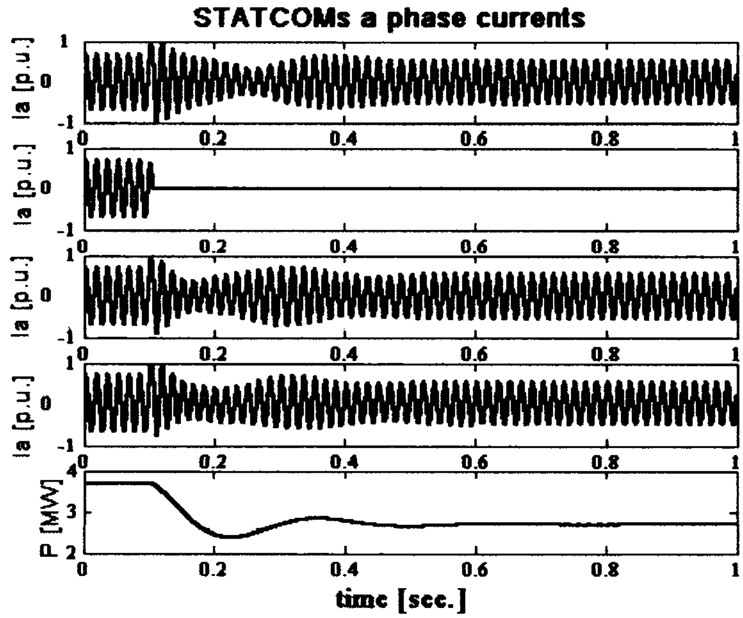


Figure 36 b) Phase-a current of every STATCOM. The lowest trace shows the power transferred over the transmission line.

4.9.1 Bulk vs Distributed SVS

Fig. 37 repeats the simulations of Fig. 35 with the important difference that all the distributed STATCOMS are lumped together as a single bulk STATCOM (as would be used if the compensation is on the high voltage side without satisfying the N-1 reliability criterion). After the sudden loss of the STATCOM, all the load bus voltages drop instantaneously for about 15 % as shown in Fig. 37 a). Fig.37 b) shows the phase-a current of the STATCOM, the reactive power flow of the load substation, the induction motor power and the induction motor slip (lowest trace). As the load has a large induction motor component, the large inductive var causes the load bus voltages to continue dropping as are evident from the gradual descending slopes in Fig. 37 a). This is because the lowering of the terminal voltage slows the induction motors further, increasing their slip and inductive var, as shown in Fig. 37 b). The positive feedback aggravation eventually leads to voltage collapse. Fig. 37 shows that when bulk SVS is used on the high voltage side, N-1 reliability criterion requires at least 2 units.

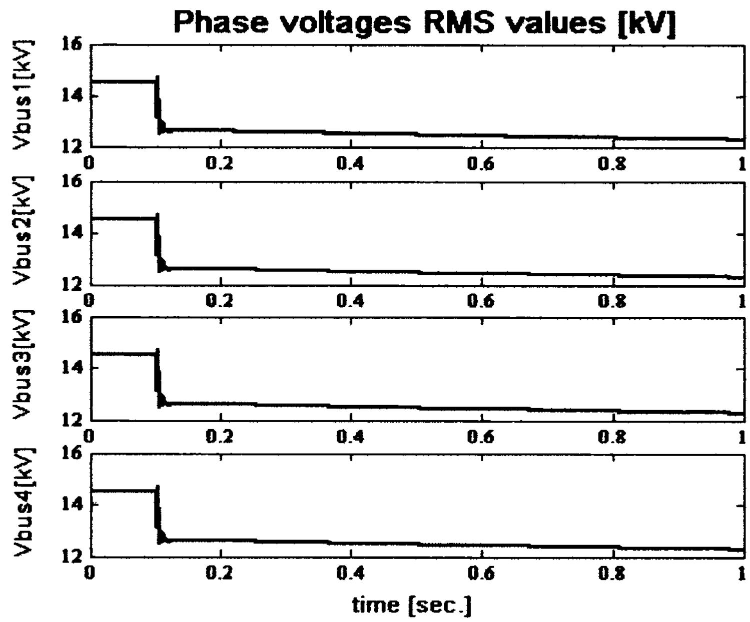


Figure 37 a) Phase voltages (rms) of 25 kV bus when single bulk STATCOM providing voltage support to 315 kV bus is lost

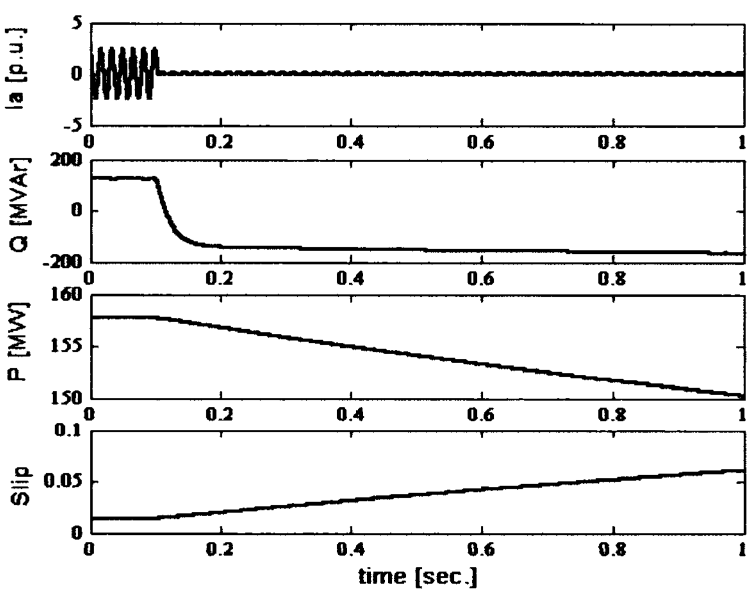


Figure 37 b) Phase-a current of bulk STATCOM, reactive power flow through the substation, active power drawn by the induction motor and motor slip

4.10 Conclusion

The preliminary evaluation, based on: (1) savings in MVArs required of the SVS and (2) savings in MVAs of the transformers, has shown that distributed SVS is more advantageous than bulk SVS located at the transmission line bus. Saving from the cost of reduced redundancy to meet N-1 reliability criterion will require knowing K, the number of SVCs or STATCOMs for standby, which will be used for bulk SVS. The designers of bulk SVS will likely divide the installation after the pattern of Fig.4.8.

Preliminary transient studies have demonstrated that the many SVS units operate harmoniously together. From the positive conclusions, further in-depth studies are justified. These studies will identify unforeseen problems in load centers regulated by distributed SVS and solve them when they surface.