CHAPTER 5

DISTRIBUTED, DISTRIBUTION STATIC VAR SYSTEMS VS. LUMPED STATIC VAR SYSTEMS: AN IN-DEPTH STUDY

5.1 Introduction

In the previous chapter it has been shown that, when a load center requires SVS for voltage support, the strategy of using many smaller sized SVS located at distribution bus is advantageous over lumped compensation on transmission level. In this chapter a step further is made toward generalization of the proposed concept showing that, when a few load centers are in parallel, providing voltage regulation with many smaller sized widely distributed Static VAr Systems (SVSs) at distribution level has more advantages than a few large lumped SVSs on transmission level. The benefits obtained from distributed, distribution voltage support scheme are quantified. The feasibility and reliability of distributed voltage support scheme with SVSs based on SVCs and STATCOMs are demonstrated by detailed real time dynamic simulation.

The structure of the chapter is as follows: Section 5.2 describes general system model used later in the chapter for steady state analysis. Section 5.3 demonstrates the feasibility of distributed, distribution voltage support scheme using phasors, while in section 5.4, reliability of distributed voltage support is demonstrated. In Section 5.5, SVS rating of distributed, distribution voltage support is calculated and compared to the rating of lumped SVS put on the transmission side of the power delivery substation. To calculate the rating, distributed line parameters have been used. In Section 5.6 a rough estimate of the cost of two compensation methods and their impact on line losses is addressed. Section 5.7 compares steady state loadability limit for two compensation schemes and, finally, in Section 5.8 detailed real time dynamic simulation of a test system is performed.

5.2 System Model for Voltage Support Analysis -

In this chapter, more general model is considered consisting of K incoming transmission lines serving N equal constant power loads.

Fig.38 illustrates the case when voltage support is provided by N distributed SVSs installed on distribution side of power delivery substation. Fig. 39 illustrates the case when one lumped SVS provides voltage support on transmission side of the power delivery substation. SVS is treated as continuous source of reactive current. It consists of switched capacitors (for economy reason) in combination with STATCOM or (Thyristor Control Reactor) TCR. Distributed parameters are used to model each line. Resistive losses are neglected.

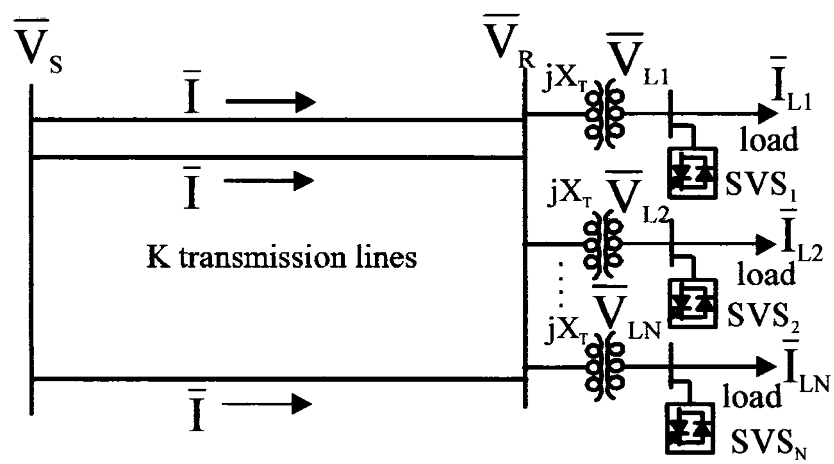


Figure 38 Single line diagram of K incoming transmission lines serving N loads over N transformers each having reactance jX_T. Each load is provided with its own SVS providing voltage support on distribution side of power delivery substation (distributed compensation).

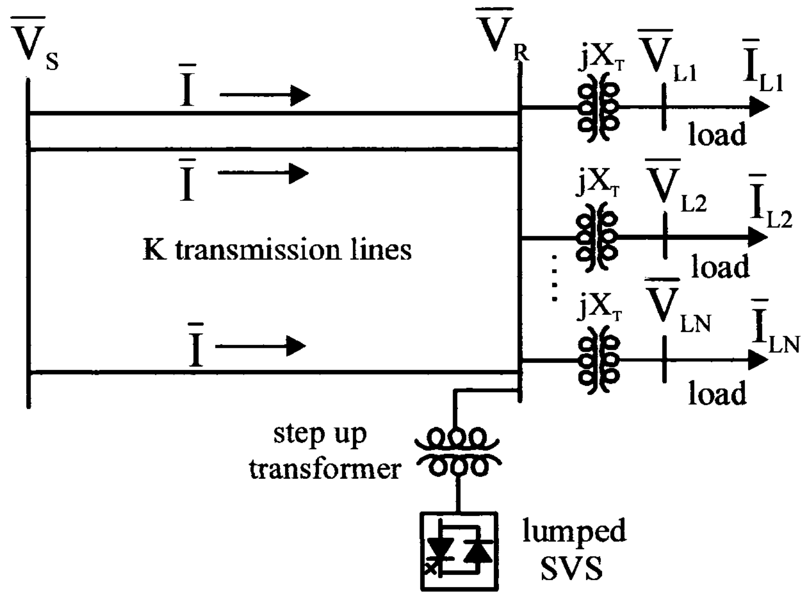


Figure 39 Single line diagram of K incoming transmission lines serving N loads over N transformers each having reactance jX_T. Voltage support is provided with one lumped SVS on transmission side of substation .

5.3 Feasibility

Before proceeding to make comparisons, it is necessary to establish that voltage support by distributed VAR compensation is mathematically feasible. This means that there are steady-state solutions for the conditions of operation. The steady-state solutions are presented here in the form of phasor diagrams. For the sake of the clarity, the number of distribution circuits is restricted to N = 3, and loads are assumed unity power factor (power factor is corrected).

5.3.1 Non-Compensated Line

The phasor diagram in Fig.40 presents the steady-state voltages and currents for non compensated line where the number of loads is N = 3. The sending end voltage $\mathbf{V_S}$ is kept at 1 p.u. due to stiffness of the system. The current $\mathbf{I} = \mathbf{I_{L1}}+\mathbf{I_{L2}}+\mathbf{I_{L3}}$ through transmission line produces a voltage drop lowering transmission side voltage $\mathbf{V_R}$. Each load current produces additional voltage drop across transformer impedances $jX_T\mathbf{I_{Li}}$ (i=1,2 and 3)

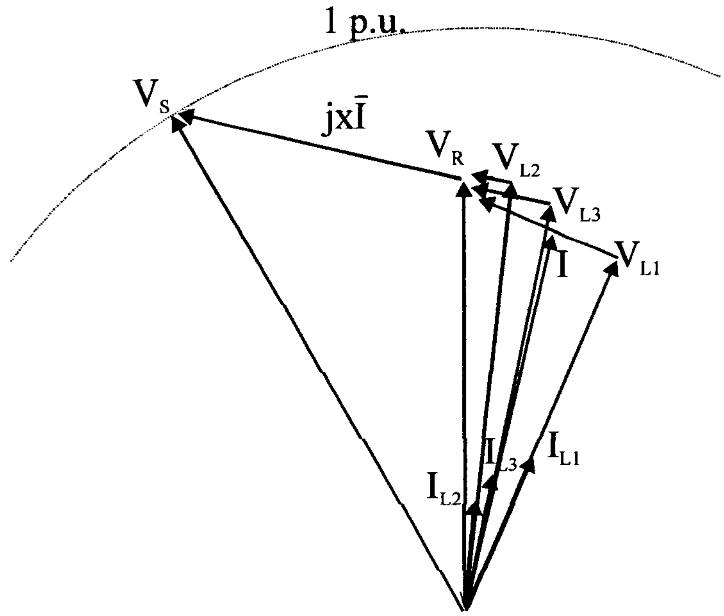


Figure 40 Phasor diagram representing current and voltages of non-compensated circuit for the case when one transmission line feeds three load centers.

5.3.2 Lumped VAR compensation

The phasor diagram in Fig.41 presents the steady-state solution for the lumped var compensation on transmission level. The sending-end voltage $\mathbf{V_S}$ and receiving-end voltage $\mathbf{V_R}$ are maintained on the circle of the 1.0 p.u. voltage radius. The closing side of the voltage triangle is the voltage phasor $j\mathbf{X}\mathbf{I}$ where $\mathbf{I}$ is the current through the transmission line. The voltage triangle satisfies Kirchhoff's Voltage Law: $\mathbf{V_S} = \mathbf{V_R} + j\mathbf{X}\mathbf{I}$. Kirchhoff's Current Law at the receiving-end bus is $\mathbf{I} = \mathbf{I_{L1}} + \mathbf{I_{L2}} + \mathbf{I_{L3}}$ where $\mathbf{I_{L1}}$, $\mathbf{I_{L2}}$ and $\mathbf{I_{L3}}$ are the load currents. For clarity, unity power factor is assumed in the loads so that the current phasors $\mathbf{I_{Li}}$ are in phase with the $\mathbf{V_{Li}}$ voltages (i=1, 2, 3). The voltage at the load bus i is $\mathbf{V_{Li}}=\mathbf{V_R} - j\ X_T\ \mathbf{I_{Li}}$, for i=1, 2, 3. It is apparent from Fig.41 that while $\mathbf{V_R}$ is regulated, $\mathbf{V_{L1}}$, $\mathbf{V_{L2}}$ and $\mathbf{V_{L3}}$ are not.

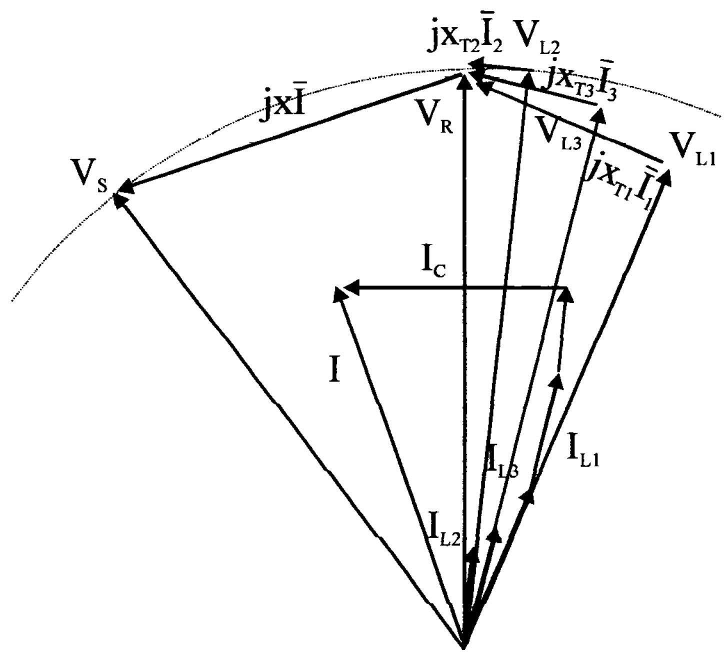


Figure 41 Phasor diagram for circuit from Fig. 39 showing voltage support from lumped compensator Compensating current $\mathbf{I_C}$, injected in quadrature with voltage $\mathbf{V_R}$.

5.3.3 Distributed VAR Compensation

The phasor diagram in Fig.42 presents the steady-state solution for the distributed var compensation of Fig.38 for N=3. It shows that even when the load currents $\mathbf{I_{L1}}$, $\mathbf{I_{L2}}$ and $\mathbf{I_{L3}}$ are not equal (evident in the phasors $j\ X_T\ \mathbf{I_{Li}}$, for i=1, 2, 3 zoomed in Fig.42), the load bus voltages $\mathbf{V_{L1}}$, $\mathbf{V_{L2}}$ and $\mathbf{V_{L3}}$ can be regulated at 1.0 p.u. The receiving-end bus voltage $\mathbf{V_R}$ has a voltage lower than 1.0 p.u.

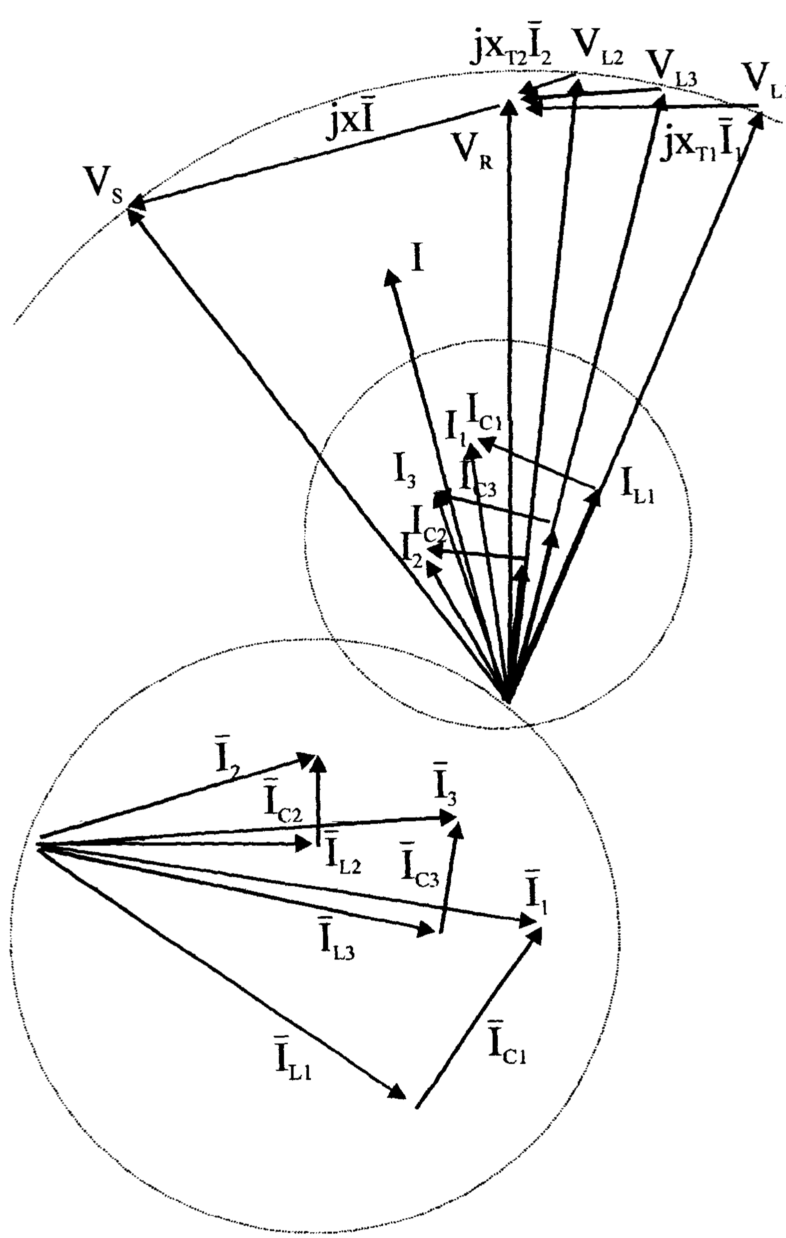


Figure 42 Phasor diagram for circuit from Fig. 38 showing voltage support from distributed compensators (SVSs or DSTATCOMs). Each SVS injects compensating current $\mathbf{I_{Ci}}$ (i=1,2 and 3), in quadrature with voltage it supports

5.4 Reliability

The loss of lumped SVS in Fig.39 (disappearance of current **Ic** on phasor in Fig.41) affects all load centers and can lead to voltage collapse. To satisfy N-1 reliability criterion there must be another stand by unit rated at the full MVAr required by the system. The loss of one of the smaller sized distributed, distribution level SVS affects only the load center that has been supported by the lost SVS and, partially, receiving end transmission voltage $\mathbf{V_R}$. However, the other distributed SVSs will indirectly support transmission voltage $\mathbf{V_R}$ and voltage on the bus where SVS has been lost.

Fig.43 describes the loss of SVS regulating load bus voltage $\mathbf{V_{L3}}$. Its loss makes compensating current I_{C3} equal to zero. As a consequence, the line current **I** decreases and rotates. The voltage $\mathbf{V_S}$ is kept at 1 pu due to stiffness of the system. Vector **jXI** (representing line voltage drop) rotates, decreasing voltage $\mathbf{V_R}$ on transmission side of the substations. Due to decrease in $\mathbf{V_R}$, distribution side voltages (load voltages) $\mathbf{V_{Li}}$ (i=1,2,3) sag. The sag of voltage $\mathbf{V_{L3}}$ is biggest because the SVS regulating it is lost. Control system of SVSs providing voltage support of load bus voltages $\mathbf{V_{L1}}$ and $\mathbf{V_{L2}}$ detect their decrease and act fast in order to restore them at 1pu. The compensating currents $\mathbf{I_{C1}}$ and $\mathbf{I_{C2}}$ increase becoming $\mathbf{I_{C1}}^{NEW}$ and $\mathbf{I_{C2}}^{NEW}$,respectively, (new SVSs compensating currents) providing additional voltage boost. The line current **I** increases rotating voltage drop **jXI**. This increases transmission voltage $\mathbf{V_R}$ but not on the same level as before the loss of the SVS, increasing load bus voltage $\mathbf{V_{L3}}$. The voltages $\mathbf{V_{L1}}$ and $\mathbf{V_{L2}}$ are restored at 1pu. Voltage $\mathbf{V_{L3}}$ stay depressed, but it is indirectly supported due to increase in transmission voltage $\mathbf{V_R}$. New steady state solution is shown in Fig.43. It is clear that the loss of one distributed SVS can be partially mitigated by the action of the other SVSs those stay into the system.

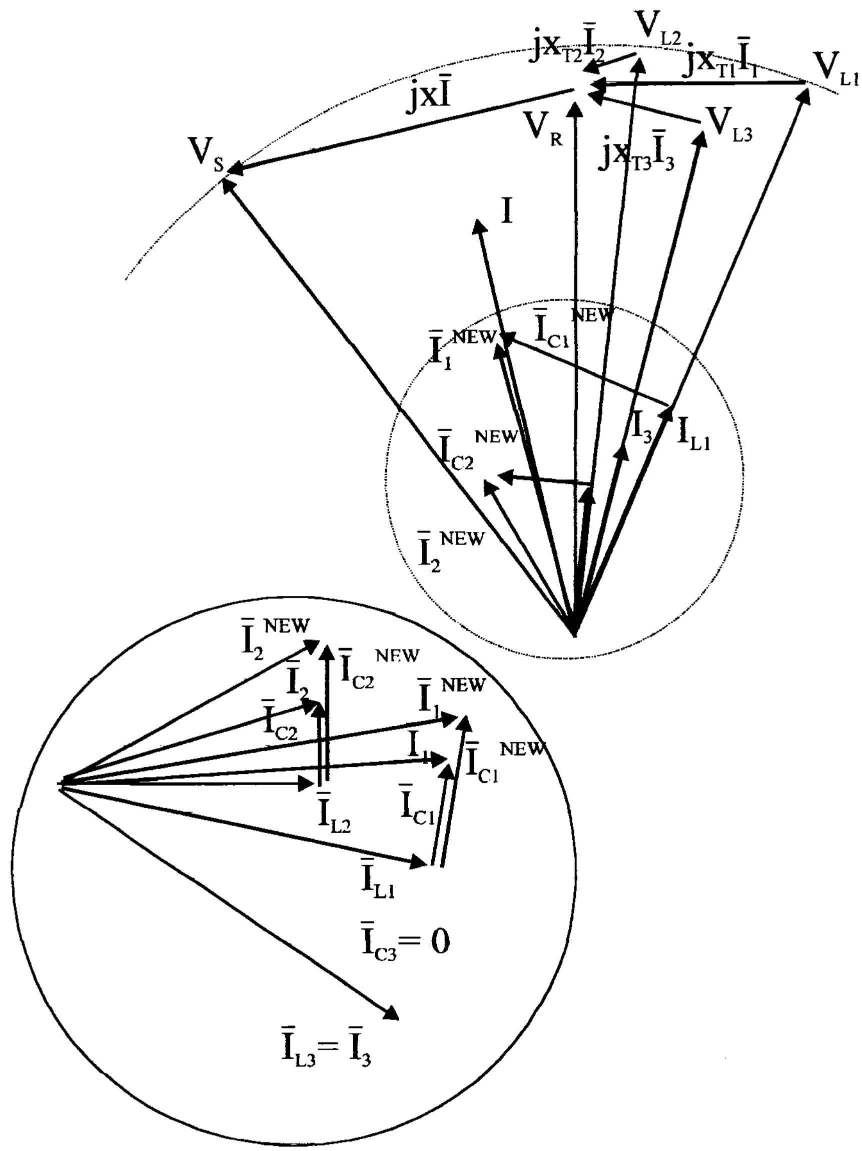


Figure 43 Phasor diagram showing steady state voltages and currents after SVS_3 is lost. Control circuits of SVS_1 and SVS_2 detect voltage drop on bus1 and bus 2 respectively. The control action of SVS_1 and SVS_2 increase its support in order to restore distribution voltages $\mathbf{V_{L1}}$ and $\mathbf{V_{L2}}$ at 1 p.u. As a consequence transmission voltage $\mathbf{V_R}$ and distribution voltage $\mathbf{V_{L3}}$ are indirectly supported.

Following example illustrates advantage of distributed, distribution side, voltage support scheme. Consider 100 km transmission line feeding three loads with powers 1.3, 0.5 and 1 p.u. over three bulk power delivery transformers. Each transformer has reactance of 0.1

p.u. and rating of 1.3 p.u. Surge impedance load P_{SIL} is used as 1 p.u.. Line reactance is 0.0013*l* where *l* is line length in km. When voltage support is provided with three distribution, distributed SVSs as in Fig. 42, reactive power needed to keep distribution voltages $\mathbf{V_{L1}}$, $\mathbf{V_{L2}}$ and $\mathbf{V_{L3}}$ at 1 p.u. is 0.25, 0.19 and 0.22 p.u. respectively. Transmission side voltage V_R is 0.986 p.u. If voltage support is provided with one lumped compensator on transmission side, as shown on Fig.41, reactive power Q_l needed to keep transmission side voltage $\mathbf{V_T}$ at 1p.u. is 0.755 p.u. which is 14% more. After the loss of Q_l supplied by lumped SVS on transmission side of power delivery substation, voltage collapse can happen.

If, for example, SVS_3 on distribution side is lost, as shown in Fig. 43, SVS_1 and SVS_2 respond immediately trying to restore voltages $\mathbf{V_{L1}}$ and $\mathbf{V_{L2}}$. In this case transmission side voltage $\mathbf{V_R}$ settles at 0.98 p.u., $\mathbf{V_{L3}}$ settles at 0.97 p.u. and I_{C1}^{NEW} and I_{C2}^{NEW} are 0.286 and 0.25 p.u, respectively.

5.5 SVS Rating

In this study per unit base is used and resistive losses are neglected. All loads in Fig.38 and Fig.39 are assumed equal, unity power factor. If the loads are not unity power factor then reactive power needed for power factor correction has to be accounted for separately. Each load draws the same current from the load bus. Due to unity power factor, distribution voltages $\mathbf{V_{Li}}$ and load currents $\mathbf{I_{Li}}$ are collinear. The real power supplied to each load is KP/N (K lines, each line delivering power P to N loads). The load current is $|\mathbf{I_{Li}}| = KP/N|\mathbf{V_{Li}}|$. Each SVS is represented as a source of reactive current. In the case of N distributed SVSs as in Fig.38, each SVS_i (i=1,...N) supplies reactive current $\mathbf{I_{Cdi}} = \mathbf{I_{Cd}}/N$. In the case of one lumped SVS as in Fig.39, the reactive current for voltage regulation is $\mathbf{I_{Cl}}$. For transmission lines representation, distributed parameters have been used. Transformers are assumed to have leakage reactances 10% on the transformer base, same as earlier case.

5.5.1 Per Unit Normalization

All quantities in Fig.38 and Fig.39 are normalized according to Table II so that results are general and valid for different voltage levels.

Table II

Per unit normalization

Nominal Voltage l-l [kV]V_{BASE}	230 [kV]	345 [kV]	500 [kV]	765 [kV]
$P_{SIL} = S_{BASE}$ [MW]	140	420	1000	2280
$Z_{BASE} = V^2_{BASE}/S_{BASE} = Z_C$[Ohm]	377.8	283.4	250	256.6

Natural load P_{SIL} is 1 (p.u.). $P_{max} = MP_{SIL} = M$ (p.u.) is maximum power to be transferred over one transmission line. Bulk power delivery transformer impedance is assumed to be 10% on the transformer base. In case of one incoming line, one substation, $X_T = 0.1/M$ (pu). In case of K incoming transmission line - N outgoing distribution circuit, $X_T = 0.1N/MK$(pu). Transformer reactance changes with transformer rating. The load is assumed to be constant power. In case of K incoming lines - N outgoing distribution lines serving N loads, $R_{Li} = N|\mathbf{V}_{Li}|^2/PK$ (pu) when distribution voltages $\mathbf{V}_{Li}$ (i=1,2...N) are kept at 1pu and the power transfer over each line is assumed to be P p.u. Total power supplied to load with K transmission line is then KP p.u. The total load equivalence, as in Fig.44 a) and 44 b), is $R= |\mathbf{V}_L|^2/PK$. When voltage support is provided on distribution side as in Fig.44 a), $|\mathbf{V}_L| = 1$p.u. and load R=1/KP. When voltage support is provided on transmission side as in Fig.44 b), the distribution voltage $|\mathbf{V}_L|$ is calculated from Fig.44 b). In this case the load current $\mathbf{I}_L = KP/\mathbf{V}_L$. Hence applying Kirchhoff's laws on circuit in Fig. 44 b), $\mathbf{V}_R = j(X_T/KM)\mathbf{I}_L + \mathbf{V}_L$:

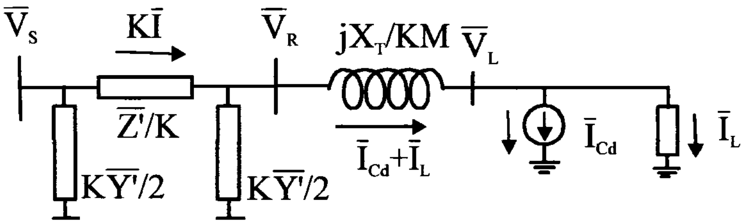


Figure 44 a) Single line diagram with N loads of Fig.38 equivalenced as a single load carrying current $\mathbf{I_L}$. Distributed SVS located at a load bus of $\mathbf{V_L}$.

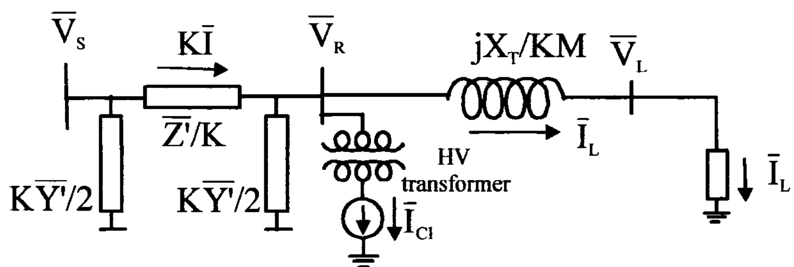


Figure 44 b) Single line diagram with N loads of Fig. 39 equivalenced as a single load carrying current $\mathbf{I_L}$. Lumped SVS connected to bus of $\mathbf{V_R}$ by additional step up transformer.

$$|\overline{V}_R|^2 = \left|\frac{X_T}{MK}\frac{KP}{|\overline{V}_L|}\right|^2 + |\overline{V}_L|^2 \tag{5.1}$$

solving (5.1) and choosing appropriate solution

$$|\overline{V}_L| = \sqrt{\frac{|\overline{V}_R|^2 M^2 + \sqrt{|\overline{V}_R|^4 M^4 - 4M^2P^2X_T^2}}{2M^2}} \tag{5.2}$$

Therefore, for constant power load:

$$R = \frac{|\overline{V}_L|^2}{KP} = \frac{|\overline{V}_R|^2 M^2 + \sqrt{|\overline{V}_R|^4 M^4 - 4M^2 P^2 X_T^2}}{2KPM^2} \tag{5.3}$$

Transmission lines are assumed lossless, therefore:

$$\overline{Z}' = jZ_C \sin \beta l \tag{5.4}$$

$$\frac{\overline{Y}'}{2} = j\frac{1}{Z_C} tn\frac{\beta l}{2} \tag{5.5}$$

Where, $\beta = \omega\sqrt{L'C'}$ is wave number and l is line length in km and Z_C is line characteristic impedance . When normalized, (5.4) and (5.5) become (5.6) and (5.7), respectively:

$$\overline{Z}'(p.u.) = j\sin \beta l \tag{5.6}$$

$$\frac{\overline{Y}'}{2}(p.u.) = jtn\frac{\beta l}{2} \tag{5.7}$$

5.5.2 SVS Rating

When lumped SVS provides voltage support, as in Fig.44 b), its objective is to keep transmission voltage $\mathbf{V_R}$ at 1 p.u. Then, the distribution side voltage has to be regulated, additionally, by other means. When voltage support is provided on distribution side of power delivery transformer as in Fig.44 a), distribution side voltage $\mathbf{V_L}$ is regulate at 1 p.u. and transmission side voltage does not have to be additionally regulated.

Applying Kirchhoff's laws on circuits in Fig.44 a) and 44 b) under the above cited conditions, following results are obtained:

5.5.2.1 Lumped Compensation

Reactive current provided by lumped SVS, needed to keep transmission voltage $\mathbf{V_R}$ at 1pu in Fig.44 b), is given by:

$$I_{Cl} = K\left(\frac{1}{\sin \beta l} + \frac{2P^2 X_T}{M + \sqrt{M^2 - 4P^2 X_T^2}} - tn\left(\frac{\beta}{2} l\right) - \frac{\sqrt{1 - \left(P \sin(\beta l)\right)^2}}{\sin \beta l}\right) \quad (5.8)$$

Reactive power of lumped SVS is given by:

$$Q_l = \left|\bar{V}_R\right|\left|\bar{I}_{Cl}\right| \quad (5.9)$$

Where $|\mathbf{V_R}|$=1pu.

Distribution side voltage $|\mathbf{V_L}|$ is obtained from (5.2) knowing that $|\mathbf{V_R}|$=1pu and is given by:

$$\left|\bar{V}_L\right| = \sqrt{\frac{M^2 + \sqrt{M^4 - 4M^2P^2X_T^2}}{2M^2}} \quad (5.10)$$

5.5.2.2 Distributed Distribution Compensation

The magnitude of reactive current provided by distributed SVSs on distribution side of power delivery transformer in Fig.44 a) is given by:

$$I_{Cd} = K\frac{\left|\bar{V}_L\right|\left(1 - \sin(\beta l) tn\left(\frac{\beta l}{2}\right)\right)}{\sin(\beta l) + \frac{X_T}{M} - \sin(\beta l) tn\left(\frac{\beta l}{2}\right)\frac{X_T}{M}} - K\frac{\sqrt{1 - \frac{P^2}{\left|\bar{V}_L\right|^2}\left(\sin(\beta l) tn\left(\frac{\beta l}{2}\right)\frac{X_T}{M} - \sin(\beta l) - \frac{X_T}{M}\right)^2}}{\sin(\beta l) + \frac{X_T}{M} - \sin(\beta l) tn\left(\frac{\beta l}{2}\right)\frac{X_T}{M}} \quad (5.11)$$

The reactive power needed for distribution voltage regulation is:

$$Q_d = \left|\bar{V}_L\right|\left|\bar{I}_{Cd}\right| \quad (5.12)$$

The complete derivations of equations (5.8) and (5.11) are given in the Appendix B. The equations (5.8) and (5.11) are general. They apply to all voltage levels, power transferred over the line, and line lengths. Fig. 45 a) to 45 e) show ratings of lumped SVS and distributed SVS plotted against line length in km for different ranges of power transferred over the line. Distribution side voltage V_L is regulated at 1 p.u. with distribution, distributed SVS. When voltage support is provided on transmission side of power delivery substation, transmission voltage V_R is kept at 1 p.u. The reactive power needed for load power factor correction has to be accounted for separately. Fig.45 shows how reactive power needed for voltage support varies as function of line length and power transferred over the line.

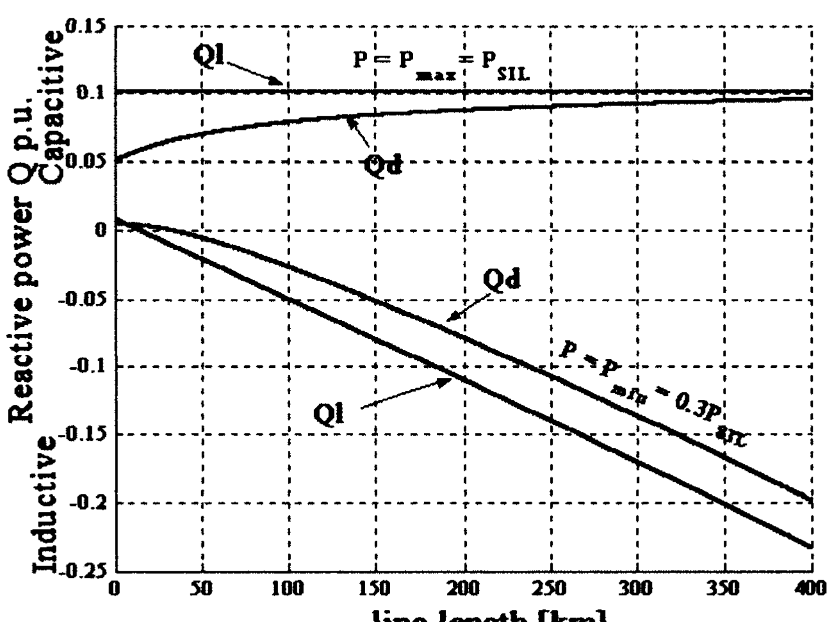


Figure 45 a) Reactive power in p.u. is plotted against line length. The power supplied to load centers vary from 0.3 p.u. to 1p.u., with unity power factor.

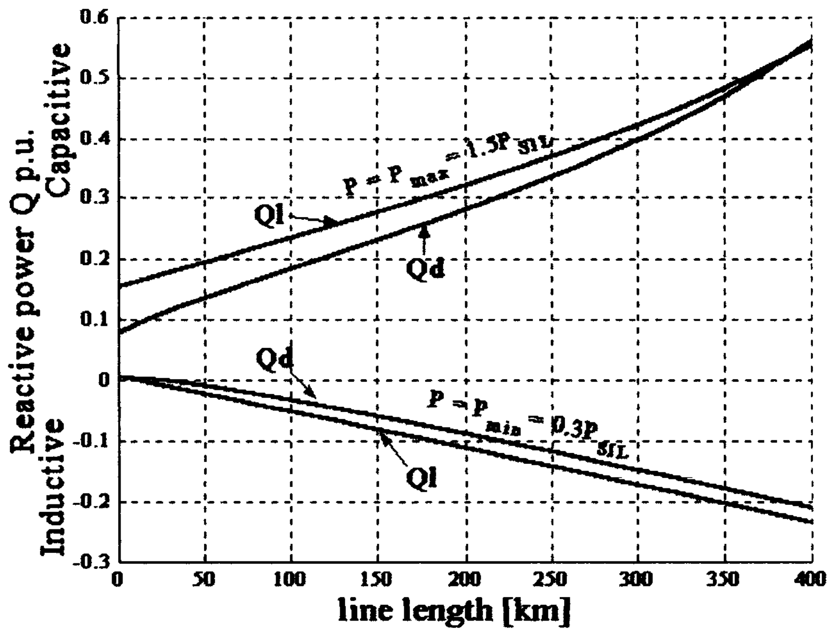


Figure 45.b) Reactive power in p.u. is plotted against line length. The power supplied to load centers vary from 0.3 p.u. to 1.5p.u., with unity power factor.

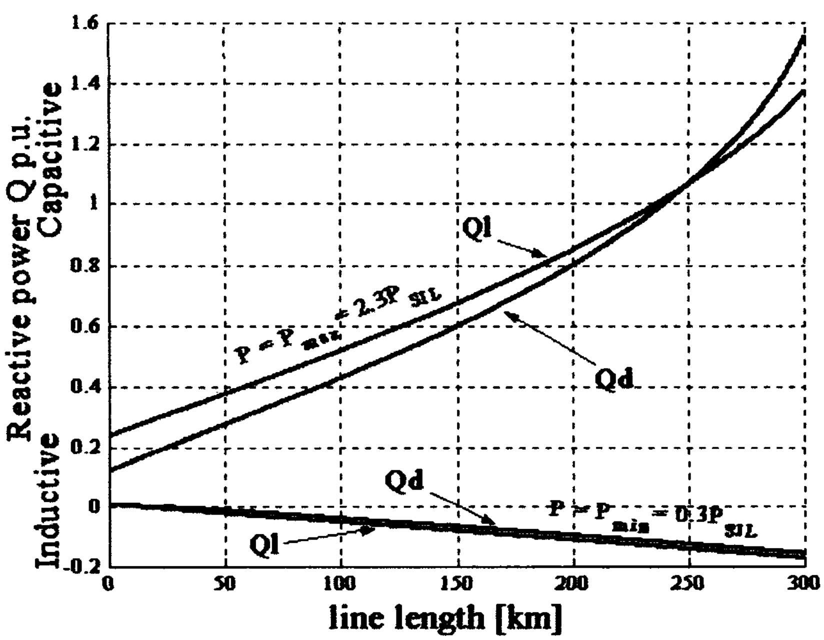


Figure 45.c) Reactive power in p.u. is plotted against line length. The power supplied to load centers vary from 0.3 p.u. to 2.3 p.u., with unity power.

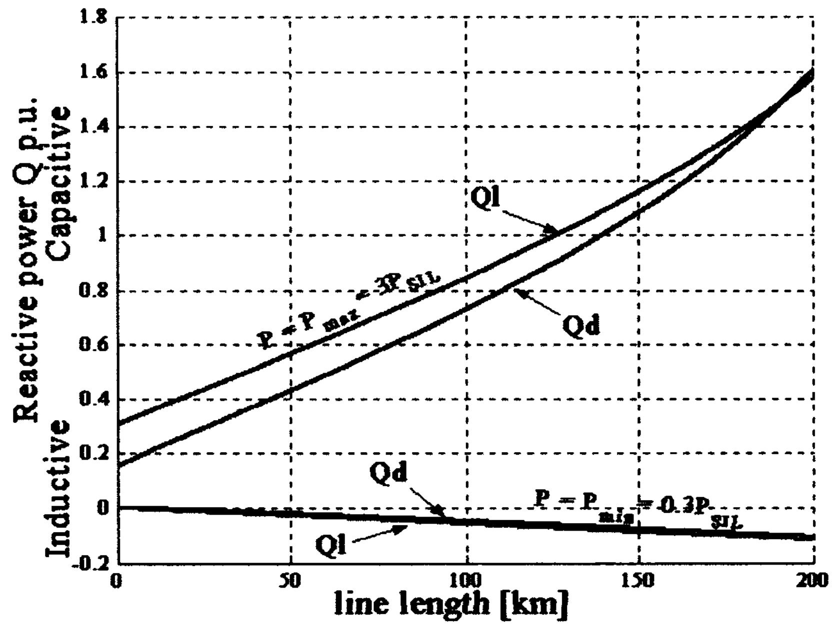


Figure 45.d) Reactive power in p.u. is plotted against line length. The power supplied to load centers vary from 0.3 p.u. to 3 p.u., with unity power factor.

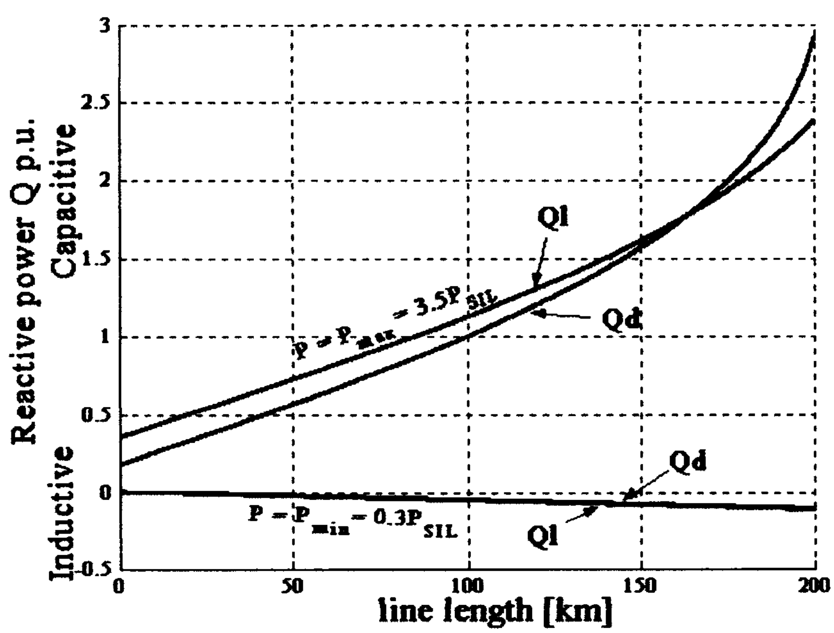


Figure 45.e) Reactive power in p.u. is plotted against line length. The power supplied to load centers varies from 0.3 p.u. to 3.5p.u. with unity power factor.

Table III

Reactive power requirements for voltage support when voltage support is provided on transmission side (TS) and on distribution side (DS)

reactive power requirements	line length [km]	position	maximum power transferred over the line [p.u.] P_{SIL} =1p.u				
			1.5	**2.0**	**2.5**	**3.0**	**3.5**
	100	TS	0.23	0.4	0.6	0.84	1.12
		DS	0.18	0.32	0.5	0.72	0.995
	200	TS	0.32	0.62	1.02	1.57	2.38
		DS	0.28	0.57	0.98	1.6	2.91
	300	TS	0.42	0.92	1.83	-	-
		DS	0.39	0.93	-	-	-
	400	TS	0.55	-	-	-	-
		DS	0.56	-	-	-	-

The results shown in Fig.45 indicate that there is a point beyond which voltage support on distribution side becomes less efficient in terms of vars than voltage support on transmission side. When compensator needed for absorption of reactive power, it is always more efficient to put it on distribution side.

5.6 Cost of Compensation

5.6.1 Cost of Mvars

The cost of compensation depends on compensation equipment used, overrating capability of compensation equipment, power transferred over the line, line length, line parameters, level of competition and overall economical situation. Cost estimates for STATCOM, SVC and Mechanical Switched Capacitors (MSC) are given in [69,70] are 50$/kVar, 40$/kVAr and 8$/kVAr, respectively. Table IV shows the difference in dollar value between two compensation methods for 500 kV line for different compensation equipment used. Savings are calculated as difference between vars required to keep transmission side of substation voltage V_R at 1 p.u when compensator installed on transmission side of substation and vars required to keep distribution side of substation voltage V_L at 1 p.u. with compensator on distribution side of substation multiplied by dollar value of MVAr. These cost estimates are based on 1996 data. Here, they are given as a guidance only. Only the manufacturers of the equipment can give exact cost.

For costs reasons STATCOM and SVC are normally used only in situation where switched capacitors and reactors would not result in satisfactory system performance which is to be determined by detailed dynamic simulation on case basis.

Table IV

Difference in cost of voltage support for 500 kV line

500kV line	line length [km]	compensator used	Maximum power transferred over the line [p.u.] .] P_{SIL} =1p.u				
			1.5	**2.0**	**2.5**	**3.0**	**3.5**
savings[$ million] (Q_{lumped}- $Q_{distribution}$)*$/MVAR	**100**	STATCOM	2.6	3.9	5	5.75	6.2
		SVC	2.08	3.12	4	4.6	5
		MSC	0.42	0.62	0.8	0.92	1
	200	STATCOM	2	2.65	2	-1.5	-26.5
		SVC	1.6	2.12	1.6	-1.2	-21.1
		MSC	0.32	0.42	0.32	-0.24	-4.2
	300	STATCOM	1.3	-0.5			
		SVC	1.04	-0.4			
		MSC	0.21	-0.08			
	400	STATCOM	-0.35				
		SVC	-0.28				
		MSC	-0.056				

5.6.2 Cost of Transformer

When voltage support is provided on transmission side of substation with one lumped SVS, step up transformer has to be used to couple it with substation. Cost of transformer can be up to 20% of total cost of SVC. When voltage support is provided on distribution side of substation with few smaller units, there is no need for additional transformer, although, if STATCOMs are used, there is still need for coupling reactor between converter and grid.

5.6.3 Cost of Redundancy

In order to comply with N-1 reliability criterion, the rating of each SVS on distribution side has to be N/(N-1) Qd where N is number of SVS on distribution side and Qd is MVAr of all N SVSs lumped together. When voltage support is provided with one lumped SVS on transmission side of substation, loss of this unit would lead to loss of entire system. For reliability, a spare unit of the full rating should be added with its own step up transformer, doubling the cost of SVS. Even if lumped SVS is divided in few blocks of same ratings to decrease MVAr standby requirement of lumped SVS, it does not eliminate needs for additional step up transformer.

5.6.4 Line Losses

Line losses are proportional to square of the current flowing through the line.

5.6.4.1 Line Losses with Voltage support on Distribution Side of Substation

Applying Kirchhoff's current law on Fig.44 a), line current can be expressed as:

$$\bar{I} = \bar{I}_L + \bar{I}_{Cd} \tag{5.13}$$

Compensation current $\mathbf{I_{Cd}}$ is in quadrature with load current $\mathbf{I_L}$,. Therefore, using load current as reference phasor, (5.13) can be rewritten as:

$$\bar{I} = I_L + jI_{Cd} \tag{5.14}$$

Reactive current $\mathbf{I_{Cd}}$ needed for distribution voltage regulation has been calculated in (5.11), and load current I_L can be calculated as:

$$I_L = \frac{P}{|V_L|} \tag{5.15}$$

where $\mathbf{V_L}$ is distribution side voltage regulated at 1 p.u. Finally, square of line current $|\mathbf{I}|^2 = |I_{Cd}|^2 + |I_L|^2$ can be computed from (5.13),(5.14),(5.15) and (5.11).

5.6.4.2 Line Losses with Voltage support on Transmission Side of Substation

When voltage support is provided on transmission side of substation, the line current **I** can be calculated from Fig.44 b). Applying Kirchhoff's current law, it can be written:

$$\bar{I} = \bar{I}_L + \bar{I}_{Ct} \tag{5.16}$$

Compensating current I_{Ct} is given by (5.8). Load current I_L can be calculated as in (5.15), but now distribution side voltage $\mathbf{V_L}$ is not regulated at 1 p.u., but it is given by (5.10). Using transmission side voltage $\mathbf{V_R}$ as reference, load current phasor $\mathbf{I_L}$ can be represented as sum of two components, one in phase with transmission side voltage $\mathbf{V_R}$ and the second one in qudrature with it. Load current component in quadrature with transmission side voltage is $|\mathbf{I_L}|\sin\delta$ while load current component in phase with transmission side voltage is $|\mathbf{I_L}|\cos\delta$, where δ is power angle between transmission side voltage $\mathbf{V_R}$ and distribution side voltage $\mathbf{V_L}$. Power angle δ can be calculated from:

$$P = \frac{|\bar{V}_T||\bar{V}_D|}{X_T / M}\sin\delta \tag{5.17}$$

Here V_R is regulated at 1 p.u.

Compensating current $\mathbf{I_{CI}}$ is in quadrature with transmission voltage $\mathbf{V_R}$. Finally, line current **I** can be expressed as:

$$\bar{I} = |I_L|\cos\delta + j\left(I_{CI} + |I_L|\sin\delta\right) \tag{5.18}$$

and square of line current is given by:

$$|\bar{I}|^2 = \left(|I_L|\cos\delta\right)^2 + \left(I_{CI} + |I_L|\sin\delta\right)^2 \tag{5.19}$$

Ratio of the line current squared when voltage support provided on distribution side of power delivery substation, to the line current squared when compensation provided on transmission side of substation plotted against power transferred over the line for 100, 200, 300 and 400 km transmission line is given on Fig.46. From Fig.46 it can be seen that line losses are mostly lower when voltage support is on distribution side.

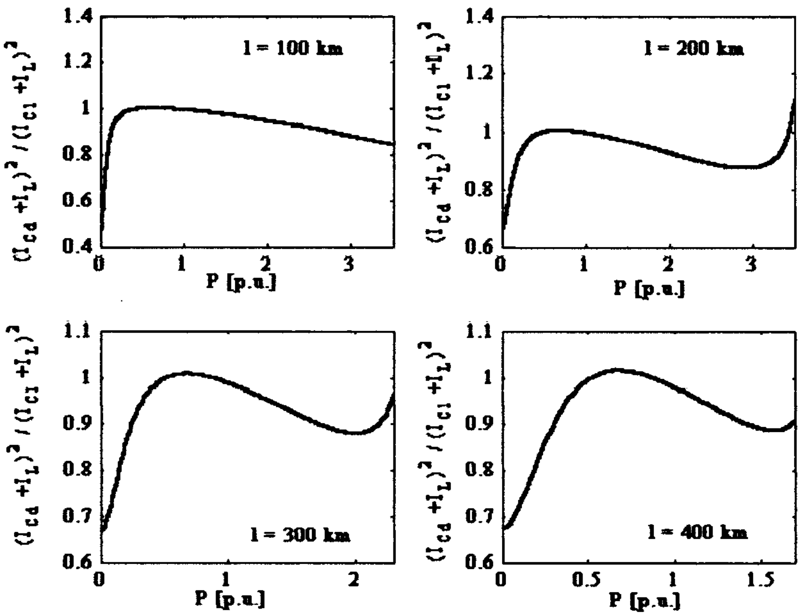


Figure 46 Ratio of the line losses when voltage support provided on distribution side of power delivery substation to losses when voltage support provided on transmission side of power delivery substation plotted against power transferred over the line for different line lengths.

5.7 Steady-State Loadability Limit

5.7.1 Uncompensated Line

Steady state loadability limit of the transmission line is determined by wave equation:

$$\overline{V}_S = \overline{V}_R \cos(\beta l) + jZ_C \sin(\beta l) \frac{P - jQ}{\overline{V}_R} \qquad (5.20)$$

Where V_S is sending end voltage fixed at 1p.u. This quadratic equation can be solved for V_R. A result is shown in Fig.47 for unity power factor (Q=0). The transformer reactance is not accounted for. Therefore, the loadability limits are even lower. Loadability limits are

3.92, 2.03, 1.44 and 1.17 p.u for 100, 200, 300 and 400 km line lengths, respectively. Surge impedance load P_{SIL} = 1p.u.

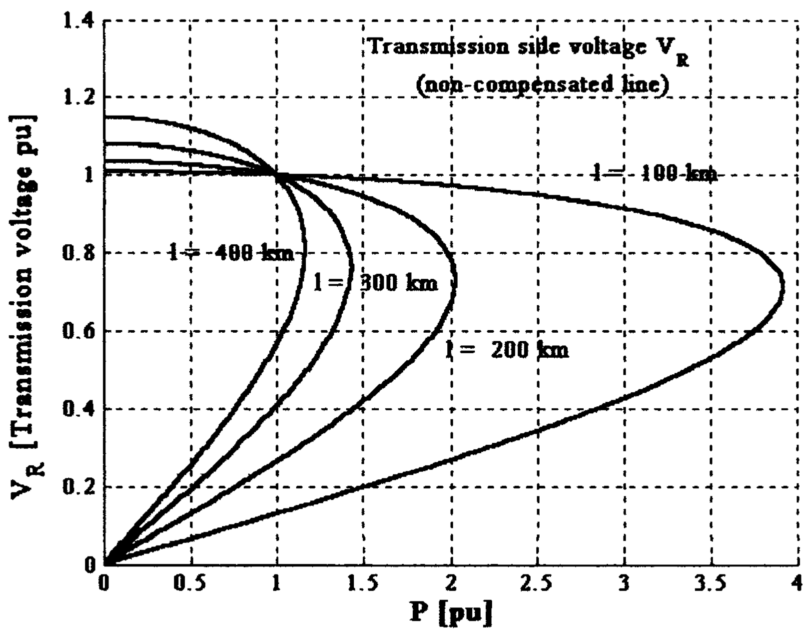


Figure 47 P-V curves for non compensated line. Surge impedance load P_{SIL} =1p.u. The effect of the transformer reactance X_T is not considered.

5.7.2 Compensated Line

5.7.2.1 Distributed SVS on Distribution Side of Substation

When distributed SVSs are sat on distribution side of power delivery substation, as in Fig. 38 (Fig.44.a)), Qd required for distribution side voltage regulation V_L is given by equations (5.11) and (5.12). Fig. 48 shows reactive power Qd needed to regulate distribution side voltage $|V_L|$ at 1.p.u. plotted versus active power P transferred over the line. The coefficient $\Delta Q/\Delta P$ (reactive power injected into the system needed to maintain distribution voltage V_L at 1p.u. for increase in power transferred over the line) is the measure of the system degradation. For theoretical loadability limit in steady state, $\Delta Q/\Delta P$ tends to infinity. It marks the point beyond which voltage regulation by shunt compensation becomes impossible (turning point on P-V curve). For practical application it is suggested that $\Delta Q/\Delta P$ should not exceed 0.9. From Fig. 48 it can be seen that steady state loadability limit is significantly increased compared to non-compensated line.

Before proceeding further, some explanations regarding Fig. 48 are required. The transformer reactance changes with transformer rating. In our calculation we assumed transformer impedance 10% on the transformer base. The maximum power delivered across the transformer is its rating. Loadability of lines changes with line lengths. For 400 km line, transformer rating is assumed to be $P_{MAX}=S_{MAX}$ = 1.5 p.u., for 300 km line P_{MAX} = S_{MAX} = 2.5p.u., and for 200 km and 100 km line P_{MAX} = S_{MAX} = 3.5 p.u., where P_{SIL} = 1p.u.. 3.5 P_{SIL} is considered to be the thermal limit of the line (X_T= 0.1/M(p.u.) where M = S_{MAX}/P_{SIL}).

5.7.2.2 Lumped SVSs on Transmission Side of Substation

When lumped SVS is situated on transmission side of power delivery substation as in Fig.39 (Fig.44 b)), Ql required for transmission voltage regulation with lumped SVS (given by equations (5.8) and (5.9)) is plotted against active power transferred over the line for different line lengths as shown in Fig.5.49. It can be seen that loadability of the lines is further increased comparing to case when voltage regulation is provided on distribution level, but not considerably. Moreover, the loading of 200 km line and shorter, is already extended to thermal limits with distribution, distributed SVS.

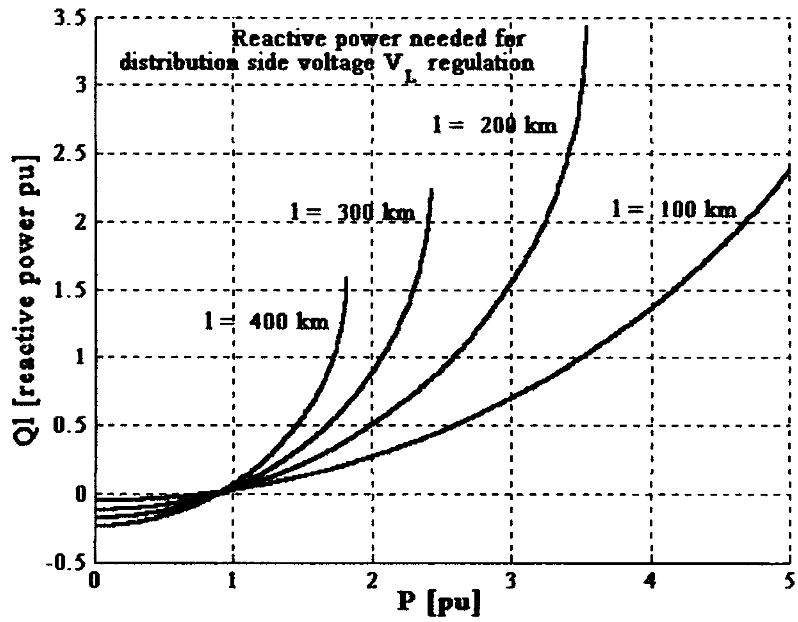


Figure 48 Qd - P curves for line compensated with distributed SVS on distribution side of power delivery substation. Surge impedance load P_{SIL} =1p.u. The effect of the transformer reactance is included.

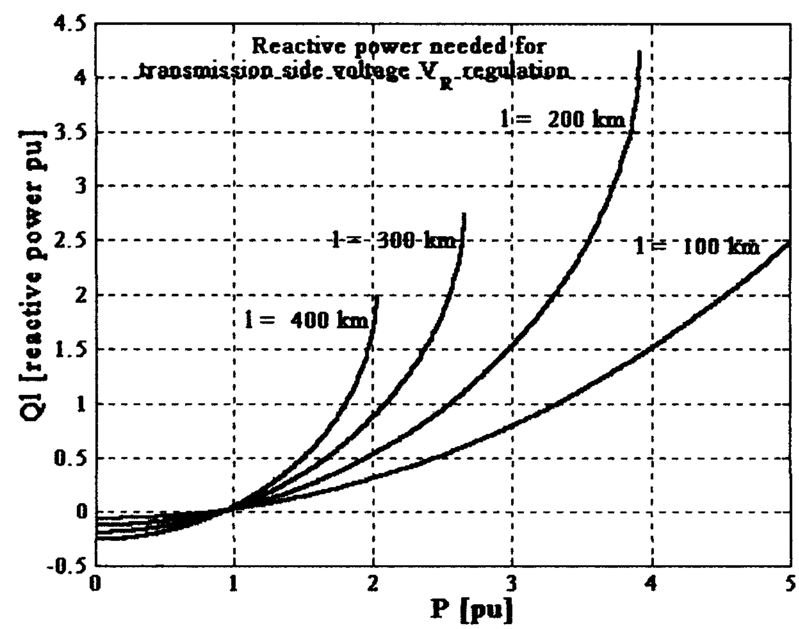


Figure 49 Ql - P curves for line compensated with lumped SVS on transmission side of power delivery substation. Surge impedance load P_{SIL} =1p.u. The effect of the transformer reactance is included.

5.8. Hypersim Digital Simulation

To demonstrate feasibility and reliability, a detailed numerical, real time simulation has been performed. Hypersim was used for this study. HYPERSIM is based on EMTP software mostly. The main advantage of HYPERSIM is availability of high precision models of lines, loads and SVCs based on experience of many years of R&D at IREQ. Importance of real time dynamic simulation is in fact that long term dynamic stability study can be performed to insure that there are no long term instabilities following contingency situations.

5.8.1 Studied System

The studied system consists of 315/25 kV, 200 km double circuit, radial transmission line delivering power to three load centers (as in Fig.38 with K=2 and N=3) shown in Fig.50. Line is transposed and each 50 km of the line is modeled with its Π nominal circuit. Load is fed over three power transformers, each rated at 400 MVA. Loads of the test system are modeled in detail. Each load is an aggregate of induction motor, static load available as default model in Hypersim, and resistive load. The active and reactive powers consumed by static load are functions of the voltage level and frequency according to (5.21) and (5.22).

$$P = P_0\left(\frac{V}{V_0}\right)^{np}\left[1 + kp\frac{f - f_0}{f_0}\right] \tag{5.21}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{nq}\left[1 + kq\frac{f - f_0}{f_0}\right] \tag{5.22}$$

Load power factor is mostly corrected with switched and fixed capacitors connected on distribution buses. The principal parameters of test system are listed in the Appendix C. Motor parameters are taken from [1]. Detailed model description is given in [72].

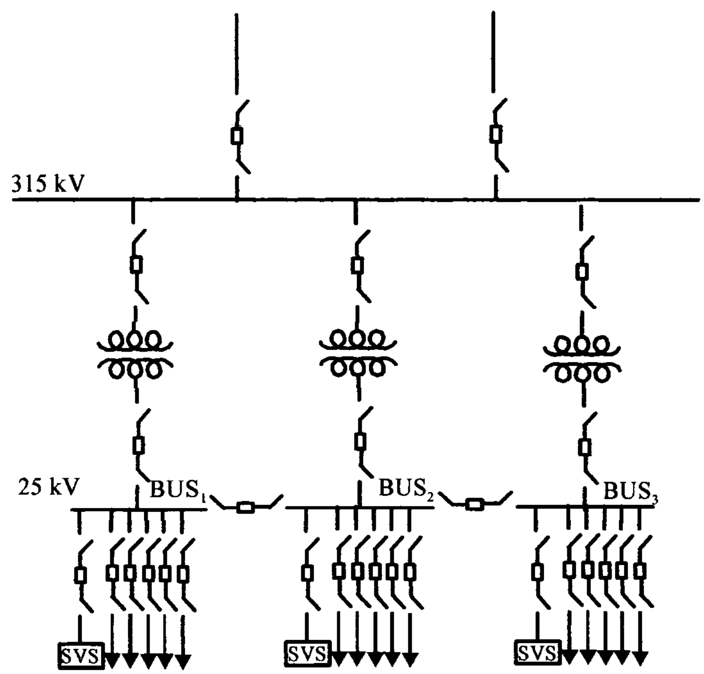


Figure 50 Test System

5.8.2 Lumped vs. Distributed Distribution SVS

First, voltage support is provided with lumped SVC consisting of three Thyristor-Switched Capacitors (TSC) circuits Y- connected and Thyristor-Controlled Reactor (TCR) delta connected. Default model of SVC with complete control and measurement system is available in Hypersim. Its detailed description is given in [72]. SVC is connected on transmission side of substation on 315 kV bus via step up transformer. Each TSC can supply 75 MVAr for total of 225 MVAr. Each branch is tuned with series reactor to 5th harmonic. Additional filtering is provided with fixed capacitor tuned to 5th and 7th harmonic. High pass filter is also added. Total power transferred over the line is 750 MW.

5.8.2.1 Loss of SVS

Fig. 51 shows the simulated waveforms of the power transferred over the lines, transmission side voltage of substation seen by SVC measurement circuit, phase ab current of one TCR and phase a currents of each TSC branch. The SVC is suddenly lost at 0.1 ms. The loss of SVC is apparent in disappearance of its currents. It can be seen that voltage drops instantaneously for about 20% and then continues to decay, leading to complete voltage collapse. It is clear that additional unit is needed as stand by with its own step up transformer to assure reliability. The same happens if SVC's transformer is lost to fault.

The same test, under the same conditions of operation is performed when voltage support is provided with three distributed, distribution SVC. Each load bus has its own SVC providing voltage support. Each SVC consists of one TCR delta connected and three branches of TSC Y-connected. Each SVC can provide total of 75 MVAr. Fig.52. a), b), and c) shows simulated waveforms for the loss of SVC_3. From Fig.52 it can be seen that voltage on load buses do not drop more then 5% and recover after 100 ms. The SVC_1 and SVC_2 respond to loss of SVC_3 with switching on their third TSC branch to compensate for the lost SVC_3. This shows the superiority of distributed, distribution voltage support scheme.

5.8.2.2 Loss of the line

The most onerous system contingency is loss of one transmission circuit. Outage of one line increases reactive and resistive voltage drop increasing reactive needs of system as it can be seen from Table III. If system is not designed with enough reactive reserve, line tripping can lead towards complete voltage collapse. Fig. 53 shows response of lumped SVC on transmission side of substation after the line tripping at 0.1 sec. Immediately after the fault, SVC undervoltage protection disconnect SVC and system voltage collapses instantaneously.

Fig. 54 shows response on same fault when voltage support is provided with three distribution side SVC, each having 75 MVAr capacity. Fig. 54 shows voltage seen by SVC measurement circuit, TCR phase current and a phase currents of each TSC branch. Each SVC responds immediately after the fault turning off TCR and switching in all TSC branches. Total power transferred over the line before line tripping is 730 MW or 2.1 p.u. After the line outage, this power is redirected over the remaining line. System is designed to support 1.5 p.u power transfer over each line for a total of 1000 MW. Due to lack of reactive power, voltage decays and stabilizes at about 0.65 p.u.. Reactive power provided by SVC decreased as a square of the voltage, clearly indicating disadvantage of impendence type compensators. They provide the least when they are most needed, showing that nameplate rating of SVCs has to be increased. After 1 sec. line is re-closed and voltage recovers but never at 1 p.u. It is worth noting that even after the line re-closing and voltage recovery the post fault conditions are not equal to pre-fault conditions as it can be seen from lowest trace of Fig. 54 a) to c). Each TSC branch of every SVC stays on and TCRs are off. This is due to increase reactive power demand from accelerating induction motors.

5.8.3 STATCOM vs SVC

The same system is simulated with the difference that all three SVCs are replaced by three lower rating STATCOMs. Each STATCOM consists of voltage controlled Voltage Source Converter and its control circuit. The control circuit is described in detail in [63] and is not available as default model in Hypersim.

Each STATCOM rating is 60 MVAr with 50% short-term overload capability. The system is subjected to line loss due to three phase short circuit fault at 0.1 sec. Each STATCOM responds immediately increasing its output current. At 1 sec.(900 msec. after the fault) the line is re-closed. Fig.55 shows the simulated waveforms of the currents of the a-phase of each distributed STATCOM and power transferred over the line. The simulated instantaneous voltage at each ac bus has been converted to rms value and displayed at Fig.56. The post-fault conditions are equal to pre-fault conditions indicating that there is no motor stalling. It can be clearly seen that lower rated STATCOMs with overload capability can perform better than SVCs.

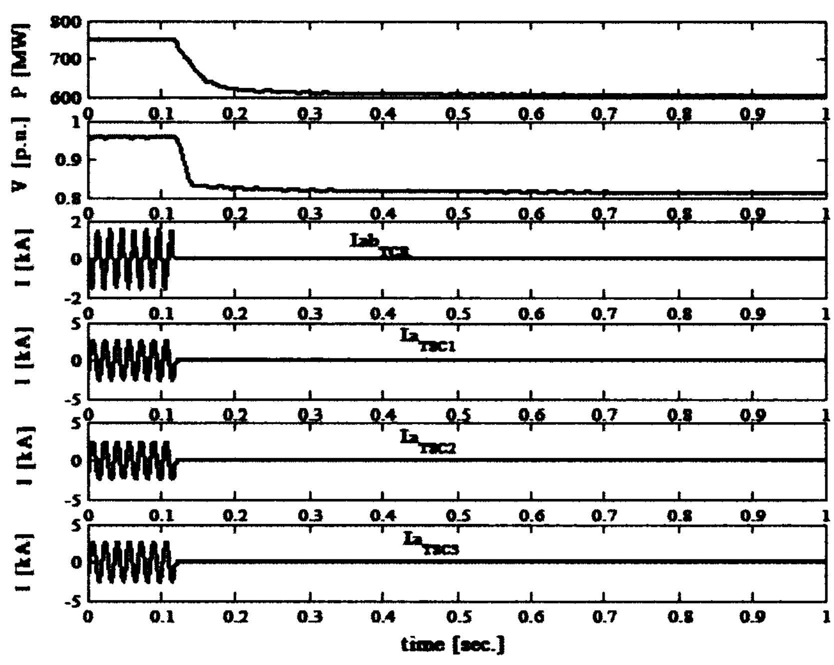
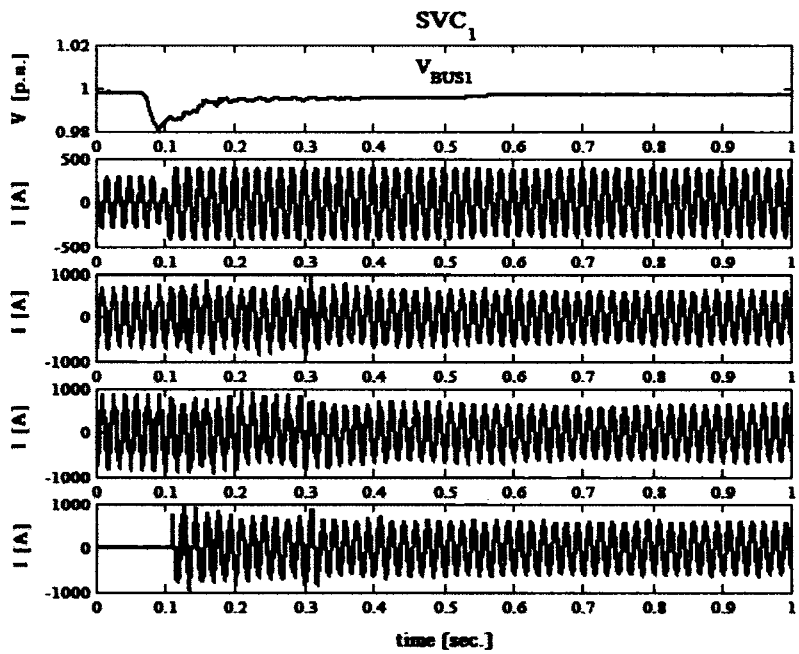
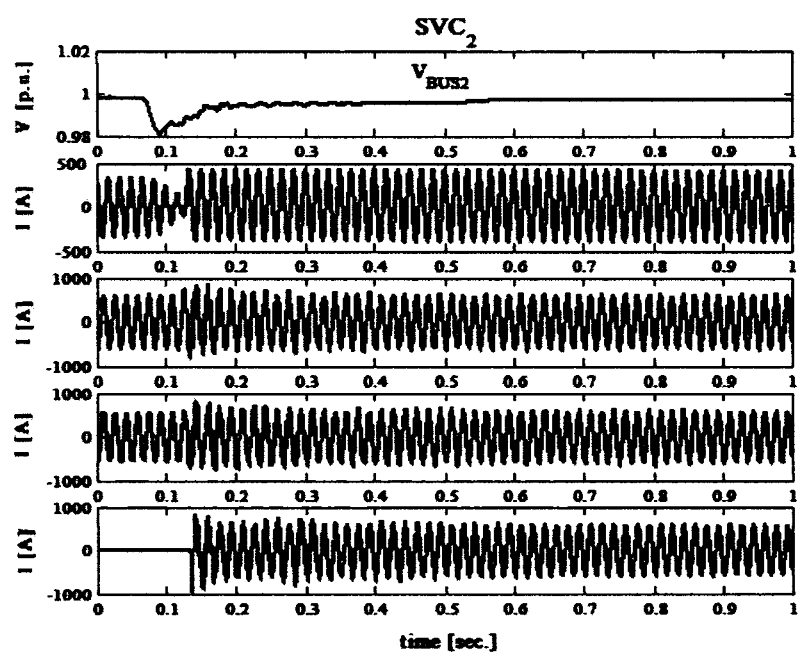


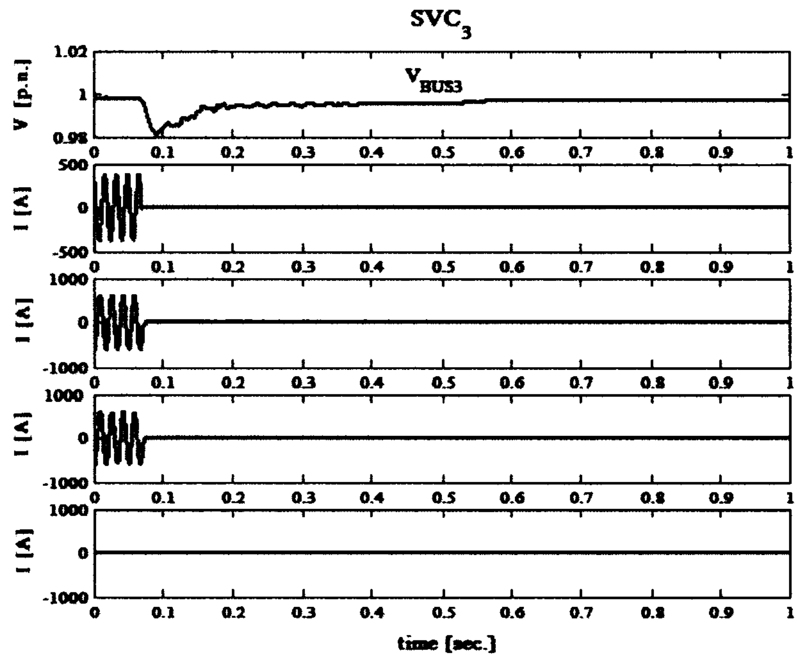
Figure 51 Transient response of studied system for loss of lumped SVC. Fig. shows power transferred over the line, transmission side substation voltage, TCR phase current and phase a currents of each SVC's branch.



(a) SVC_1 dynamic response for the loss of SVC_3.



(b) SVC_2 dynamic response for the loss of SVC_3.



(c) SVC_3 dynamic response for the loss of SVC_3.

Figure 52 Transient response of studied system for the loss of SVC

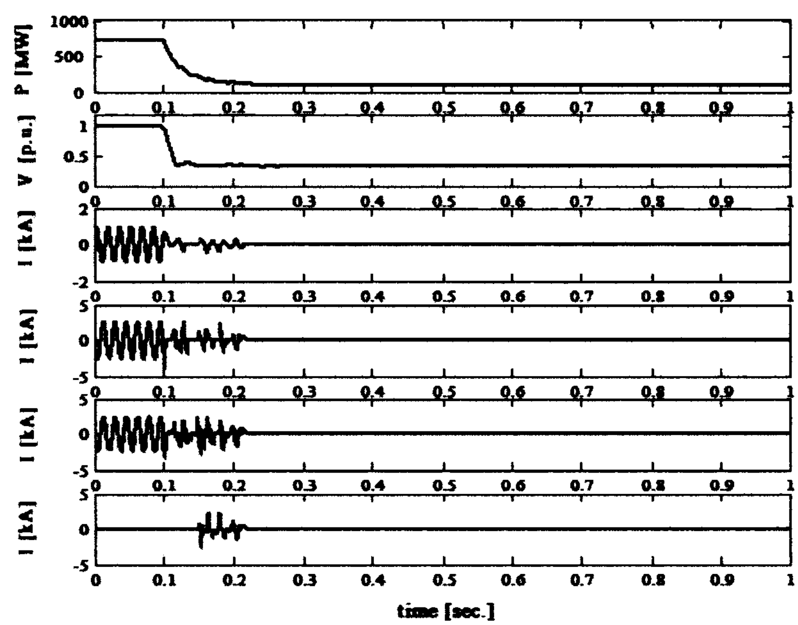


Figure 53 System transient response for one line tripping at 0.1 sec when voltage support provided with one lumped SVC on transmission side of substation.

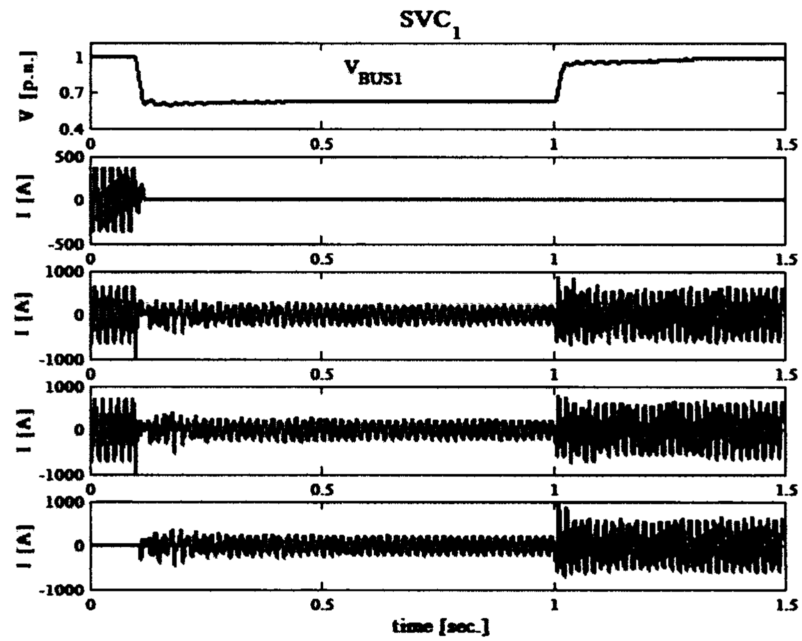


Figure 54 a) The SVC_1 dynamic response. (Bus voltage, TCR phase current and phase current of each branch of TSC).

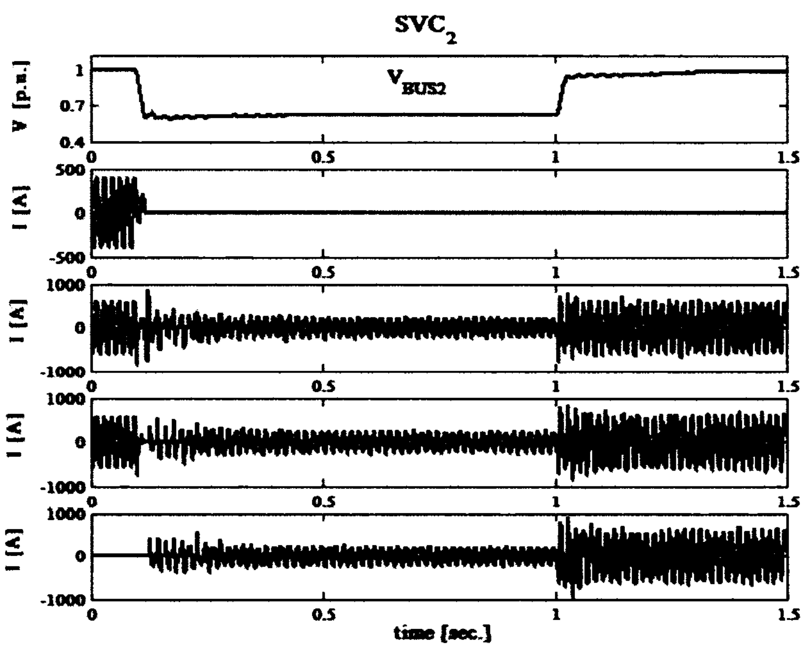


Figure 54 b) The SVC_2 dynamic response. (Bus voltage, TCR phase current and phase current of each branch of TSC).

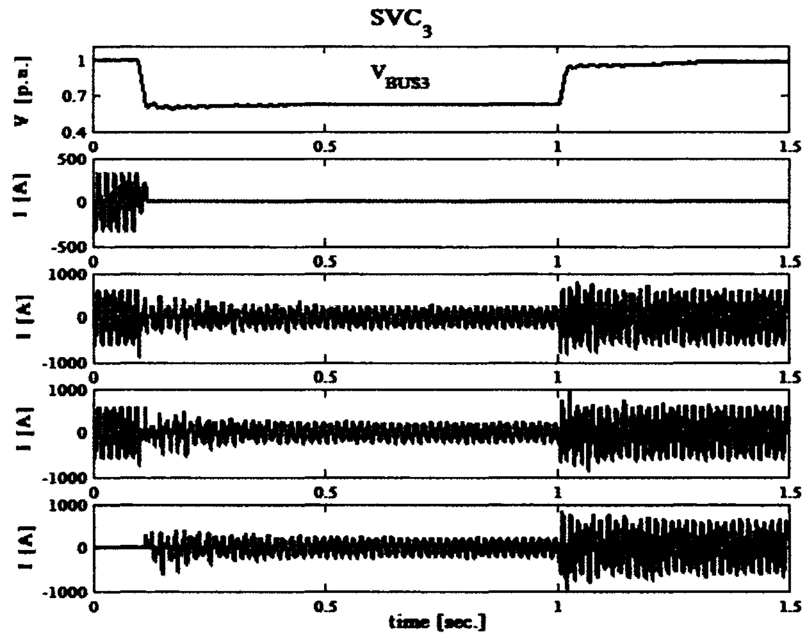


Figure 54 c) The SVC_3 dynamic response. (Bus voltage, TCR phase current and phase current of each branch of TSC). Line is lost at 0.1 sec. and re-closed at 1 sec. when voltage support provided with three distribution SVCs.

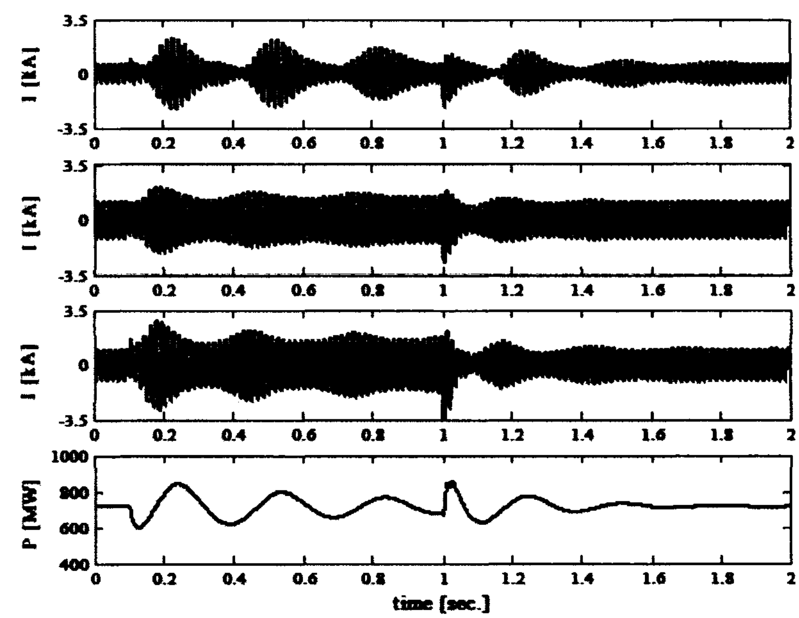


Figure 55 A system transient response when one transmission line lost at 0.1 sec. due to three phase fault. The fault is cleared and line is re-closed 900 msec. after the fault.

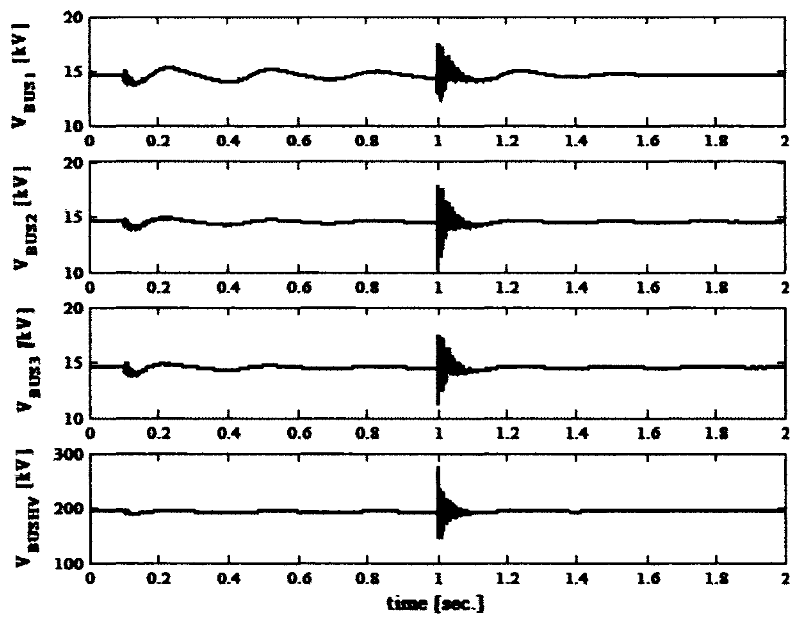


Figure 56 System transient response when one line lost at 0.1 sec. Voltage support is provided with three distribution STATCOMs. (Phase voltages (rms) of 25 kV buses and phase voltage of 315 kV bus). The faulted line is successfully re-closed at 1 sec.

5.9 Conclusions

In this chapter two voltage support schemes i) distributed, distribution compensation with large number of similarly sized SVSs providing voltage support at load centers on distribution level, versus ii) lumped compensation on transmission level with one large SVS installation, are compared. Results based on steady state analysis and detailed dynamic simulation of one equivalent test system showed a series of benefits emerging from distributed, distribution voltage support scheme. The benefits include: 1) lower VAr requirement to support load voltages, 2) better voltage regulation at load centers because each SVS regulate voltage where it is connected, 3) possibility of elimination of LTC transformers for voltage control of loads which, as consequence, decreases overall maintenance concerns, 4) not needing step up transformer to raise SVS output voltage if

SVS is installed on distribution level, 5) enhanced reliability, 6) lower standby requirement in order to satisfy N-1 reliability criterion and 7) lower line losses.
However, for each line, depending on line length and loading, there is point beyond which distribution side compensation becomes inefficient in terms of VARs needed for voltage support and line losses. Although distribution side compensation increases transmission capacity of the line, if further increase is needed, it can be obtained by transferring voltage support on transmission level. Loadability of 200 km and shorter lines can be extended to thermal limits with distribution side voltage support.

Detailed dynamic simulation of one test system has demonstrated feasibility and advantages of proposed voltage support method. Moreover, it has been shown that lower nameplate rating STATCOMs with short time overload capability can perform better then impedance based compensator devices.