CHAPTER 7

VOLTAGE SUPPORT OF LONG RADIAL TRANSMISSION LINES BY VAR COMPENSATION AT DISTRIBUTION BUSES

7.1 Introduction

The objective of this chapter is to bridge the gap between transmission and distribution approaches to voltage support and reactive power management. The impetus, which should bring transmission system engineers and distribution system engineers together, is the availability in the market of SVCs which can be connected directly to the distribution buses at voltages as high as 35 kV without step-up voltage transformers [68]. As it requires concrete examples to demonstrate how the innovative advance can be exploited, this chapter reviews where the potential benefits are and proceeds to substantiate the claims in a case study of a 400 km long, 230 kV radial line supplying 200 MW to each of 4 loads spaced evenly along its length.

The case study is patterned after Hydro-Quebec's 1000 km long James Bay line whose voltage profile is supported by a combination of capacitors and static var compensators at 5 intermediate points along the line. If the intermediate points are not in the Canadian wilderness but are in inhabited areas, the same concept can be applied to increase the transmissibility of real power to distant townships at intermediate points spread along the long line. As such a project falls within development and planning of transmission systems, the capacitors and static var compensators (SVC) will be installed on the transmission line buses.

One objective of this chapter is to highlight the advantages of distribution bus voltage support to transmission system engineers who are charged with the development and planning for the voltage support of long lines. In today's restructured electric utilities, the many distribution systems and the transmission system may belong to different owners. The technical and economic advantages can still be implemented by putting voltage support as an ancillary service. The distribution system closest to the generation source is providing capacitive reactive power not only for its own load but also for the loads of distribution systems further down the line.

It is required to show that the concept is technically feasible. This is accomplished by digital simulations. The simulation tool in use has been HYPERSIM. The successful simulation firstly implies feasibility, meaning that there is a mathematical solution of the operating point. Secondly, the operating point is steady-state stable, because otherwise there is no stable convergence in the simulations. Finally, simulations have been used to demonstrate that after three-phase-to-ground faults, the transmission line automatically recovers its regulated distribution bus voltages.

In quantifying capacitive reactive power, this chapter makes a distinction between the amount required for power factor correction and the amount required for voltage support. In order to simplify bookkeeping, the amount required for power factor correction is deducted in the accounting, so that one has a realistic value of the capacitive reactive power required for voltage support. In this chapter, to provide voltage support (VS) by var compensation, the authors use Static Var Compensators(SVC) because it is proven, mature and reliable technology.

7.2 Voltage Support of Long Transmission Line

Two transmission line voltage support schemes are presented in this section: voltage support (VS) provided by SVCs on the transmission buses and VS provided by SVCs on the distribution buses. Circle phasor diagrams are given to draw attention to the fact that, unlike distribution system engineers who are concerned only with voltage support for the loads connected to the substation, transmission system engineers have to be concerned with all the loads along the transmission line.

7.2.1 Voltage Support at Transmission Buses

Fig. 70 shows a radial transmission line made up of M sections, each of which is represented by an inductive reactance jX_i, $i=1,2,. M$. The generation source voltage is $\mathbf{V_S}$. At the i^{th} node, between two transmission line sections, the voltage is $\mathbf{V_{Ri}}$. SVC providing VS would be connected at each node to regulate the nodal transmission line voltage $|\mathbf{V_{Ri}}|$ at 1.0 pu. Because the technology of the reactive power compensation is realized at the level of distribution voltage, each installed SVC requires a step-up transformer to raise its output voltage to the transmission voltage level of $\mathbf{V_{Ri}}$. The distribution bus (voltage $\mathbf{V_{Li}}$) of the i^{th} load center is coupled to the transmission bus (voltage $\mathbf{V_{Ri}}$) by a voltage step-down transformer which is represented by its leakage reactance jX_{Ti}.

Fig.71 is a phasor diagram for the i^{th} node of Fig.70. The phasor diagram is intended as a pictorial representation of the steady-state performance of this system providing an illustration of what is happening at a glance. From Fig.71 it can be seen that, when the transmission voltages are regulated, the tips of the per-unitized transmission voltage phasors $\mathbf{V_{Ri}}$, $i=1,2..M$, lie on a circle of unit radius. The voltages of two adjacent nodes, $\mathbf{V_{Ri}}$ and $\mathbf{V_{R(i-1)}}$, form two sides of a voltage triangle in accordance to Kirchhoff's Voltage Law $\mathbf{V_{R(i-1)}}=\mathbf{V_{Ri}}+jX_i\mathbf{I_i}$ where $\mathbf{I_i}$ is the line current through jX_i, which represents the reactance of the i^{th} transmission line section. The voltage phasor $jX_i\mathbf{I_i}$ is perpendicular to the current phasor $\mathbf{I_i}$. Because of the voltage drop across the transformer leakage reactance jX_{Ti} by the load current $\mathbf{I_{Li}}$, the load voltage $\mathbf{V_{Li}} = \mathbf{V_{Ri}} - jX_{Ti}\mathbf{I_{Li}}$ is not regulated. Transformer tap changers must be employed to achieve close load voltage regulation at every node. As will be seen in Section 7.5, transformer tap changers will not be needed when the SVC regulates $\mathbf{V_{Li}}$, the distribution (load) bus voltage directly.

From Kirchhoff's Current Law at the ith node, the capacitive compensating current is: $\mathbf{I_{Ci}=I_i-I_{i+1}-I_{Li}}$. The compensating current $\mathbf{I_{Ci}}$ in Fig. 71 leads the transmission bus voltage $\mathbf{V_{Ri}}$ by 90^0. The transmission bus voltages $\mathbf{V_{R(i-1)}}$ and $\mathbf{V_{Ri}}$ lie on the unit circle. It is assumed that lagging power factor in the load has already been corrected and therefore, the load current $\mathbf{I_{Li}}$ is in phase with $\mathbf{V_{Li}}$. The line current $\mathbf{I_i}$ is the vector sum of the load current $\mathbf{I_{Li}}$, the current through i+1th segment of the line $\mathbf{I_{i+1}}$ and the compensating current $\mathbf{I_{Ci}}$.

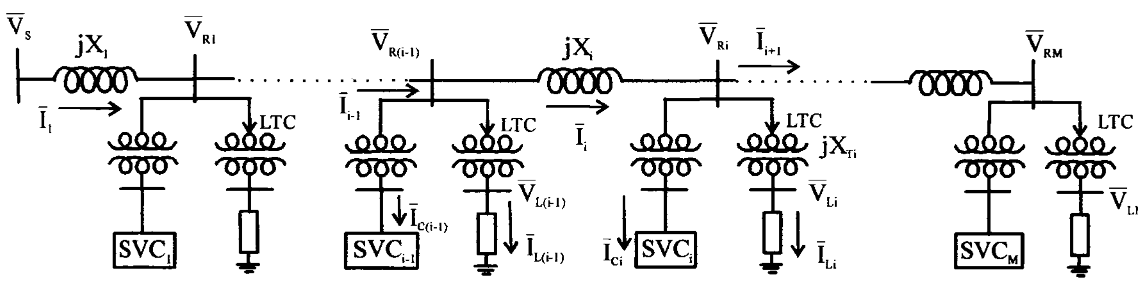

Figure 70 Single line diagram of radial transmission line feeding M load centers. Voltage support (VS) is provided on transmission buses.

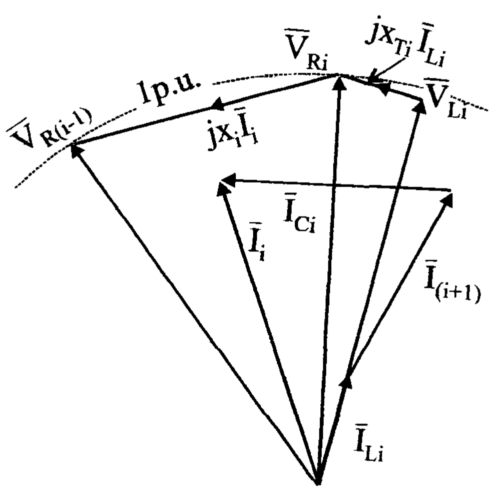

Figure 71 Phasor diagram for ith node of Fig.70

7.2.2 Voltage Support at Distribution Buses

This chapter advocates connecting the SVC providing VS to the distribution buses as shown in Fig. 72. At the ith node, SVS$_i$ is set to regulate the load voltage at $|\mathbf{V_{Li}}|$ =1.0 pu.

Fig. 73 shows the distribution bus voltages, $\mathbf{V_{Li}}$ and $\mathbf{V_{L(i-1)}}$, of the ith and (i-1)th nodes lying on the unit circle under SVC regulation. SVC$_i$, in providing voltage support to $\mathbf{V_{Li}}$, supports the transmission bus voltage $\mathbf{V_{Ri}}$ also. The compensating current of SVC$_i$, $\mathbf{I_{Ci}}$, leads the distribution voltage $\mathbf{V_{Li}}$ by 90^0. The magnitude of the transmission bus voltage, given by the formula, $|\mathbf{V_{Ri}}| = |\mathbf{V_{Li}}+jX_{Ti}(\mathbf{I_{Li}}+j\mathbf{I_{ci}})|$, is no longer at 1.0 pu. The current $\mathbf{I_{i+1}}$ further down the line joins the transmission bus to form a second node at which the current $\mathbf{I_i}=\mathbf{I_{i+1}}+\mathbf{I_{Li}}+\mathbf{I_{Ci}}$. The transmission bus voltages form a voltage triangle in accordance to Kirchhoff's Voltage Law $\mathbf{V_{R(i-1)}}=\mathbf{V_{Ri}}+jX_i\mathbf{I_i}$.

Unlike distribution system engineers who are responsible for the load current $\mathbf{I_{Li}}$, transmission system engineers have to look after the current $\mathbf{I_{i+1}}$ from further down the line also.

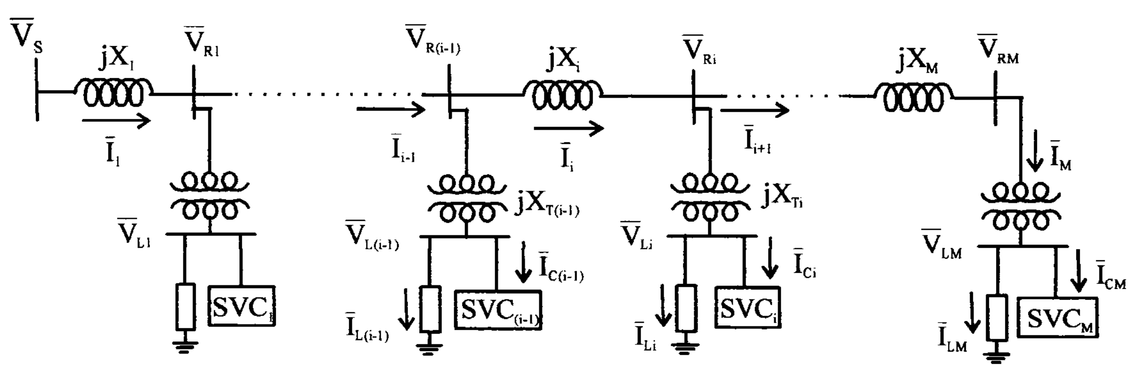

Figure 72 Single line diagram of radial transmission line feeding M load centers. Voltage support (VS) is provided on distribution buses

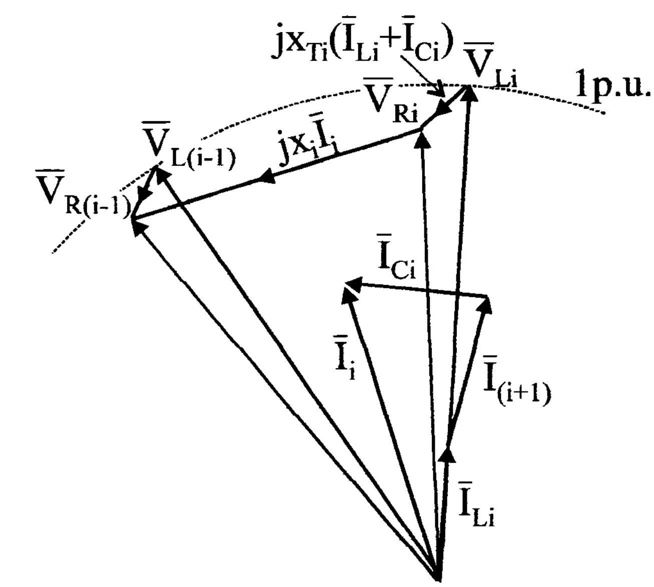

Figure 73 Phasor diagram for i[th] node of system using distribution bus VS

7.3 Comparison of Two Voltage Support Schemes

7.3.1 Transformer Savings

At each node in Fig.70, there is one transformer for the load and another transformer for the SVC. Both the load and the SVC operate at low voltages and the objective of this chapter is to point out that there is no reason to step-up the capacitive reactive power of the SVC by one transformer to transmission voltage level and then to step it down again to the distribution voltage of the load. By connecting the SVC directly at the load bus as shown in Fig. 72, the SVC transformer can be saved.

7.3.2 Providing (N-1) Reliability

There is further saving to be gained in the planning for (N-1) reliability. (N-1) reliability consideration requires that the voltage support be realized by N ($\neq 1$) units. Should any voltage support unit fail, the remaining (N-1) units must have sufficient Mvar capacity. The cost of (N-1) reliability diminishes as N increases.

7.3.2.1 Distribution Buses Voltage Support

When Q_{iD} is the total reactive power required to provide voltage support of the ith node, (N-1) reliability requires the reactive power to be divided into N_{iD} smaller units. Upon failure of any one unit, the remaining (N_{iD}-1) units still provide the amount Q_{iD}. The (N-1) reliability requirement of reactive power is therefore $N_{iD}Q_{iD}/(N_{iD}-1)$.

Such division fits naturally in the design of distribution substations. such as shown in Fig.32. 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 transmission and distribution voltage levels in order to fulfill the reliability of power supply.

In the example of Fig. 32, when the real power requirement is P_i, (N-1) reliability is satisfied by over-sizing each transformer to carry $P_i/(N_{iD}-1)$ watts (N_{iD}=4 in the example). In this situation, it is normal to allocate one SVC unit to each of the 25 kV buses. As the transformers carry the real and the reactive powers, their total MVA requirement is $N_{iD}(P_i^2+Q_{iD}^2)^{0.5}/(N_{iD}-1)$. As N_{iD} increases, their total MVA approaches $(P_i^2+Q_{iD}^2)^{0.5}$.

Furthermore, because $(P_i^2+Q_{iD}^2)^{0.5}<|P_i|+|Q_{iD}|$, when the ratio Q_{iD}/P_i is small, the rating of the step-down transformers is only slightly increased by the need to carry capacitive reactive power.

7.3.2.2 Transmission Buses Voltage Support

Using the same principle of dividing the reactive power Q_{iHV} required by the transmission bus SVC into N_{iHV} units, the total rating required to satisfy the (N-1) reliability criterion is: $N_{iHV}Q_{iHV}/(N_{iHV}-1)$ for: (i) the reactive power and (ii) the step-up transformers. On the load-side, the total MVA of the step-down transformers is $N_{iD}P_i/(N_{iD}-1)$.

7.3.2.3 Potential Reduction in Cost

In summary, the comparison of the two schemes are:

Reactive Power Requirements:

Distribution Bus SVC: $N_{iD}Q_{iD}/(N_{iD}-1)$

Transmission Bus SVC: $N_{iHV}Q_{iHV}/(N_{iHV}-1)$

Transformers MVA Requirements:

Distribution Bus SVC: $N_{iD}\,(P_i^2+Q_{iD}^2)^{0.5}/(N_{iD}-1)$

Transmission Bus SVC: $N_{iD}P_i/(N_{iD}-1)+N_{iHV}Q_{iHV}/(N_{iHV}-1)$

As will be seen in the next section, $Q_{iD}< Q_{iHV}$. Furthermore, usually $N_{iHV}<N_{iD}$ in engineering practice. Therefore, the equipment requirement is less for SVC on the distribution bus side than on the transmission bus side.

7.3.3 Reactive Power Savings

In general, $Q_{iD}<Q_{iHV}$, that is the reactive power required to provide voltage support is less when the SVCs are located at the distribution buses than at the transmission buses. However, there is a transmission length and a load limit beyond at which the inequality is reversed, i.e. $Q_{iHV}<Q_{iD}$. This transmission length is near to where voltage collapse occurs.

Approaching the problem by analysis, the point is close to the region where the solutions are complex and therefore infeasible. In such a case, VS by shunt compensation alone is not viable either on the transmission or the distribution buses. In such a situation, one should consider increasing the transmission voltage or using a combination of series and shunt compensation.

7.3.4 Line Losses

The transmission bus voltages $\mathbf{V}_{\mathbf{R(i-1)}}$ and $\mathbf{V}_{\mathbf{Ri}}$ in Fig.72 are lower than those in Fig.70. For the same real power transferred, the current $\mathbf{I}_{\mathbf{i}}$ must be higher in VS on the distribution bus than on the transmission bus and consequently this applies to the line losses. But as will be seen in the case study below, the increase in losses is not substantial.

7.3.5 Benefits

To summarize, the benefits of voltage support on distribution buses by var compensation are:

i) lower transformer MVA requirements,

ii) lower var requirement for voltage support,

iii) close voltage regulation of the loads,

iv) lower cost in assuring N-1 reliability.

7.4 Proofs of Viability of Concept

The benefits will come to naught, if the system of Fig. 72 is not technically viable in the first place. This chapter presents evidences on viability in a case study based on: (i) existence of steady-state solutions; (ii) stability of steady-state solutions; (iii) ability of the system to survive faults.

7.4.1 Case Study: 400 km Long, 230 kV Radial Line

The case study relates to the single line diagram of Fig. 74. It consists of a 400 km long, radial, single circuit transmission line feeding four load centers located at 100, 200, 300 and 400 km from the generation source. The line supplies 200 MW at each load center. The transmission line voltage is rated at 230 kV. The distribution voltage is 25 kV. The source is modeled as an infinite bus.

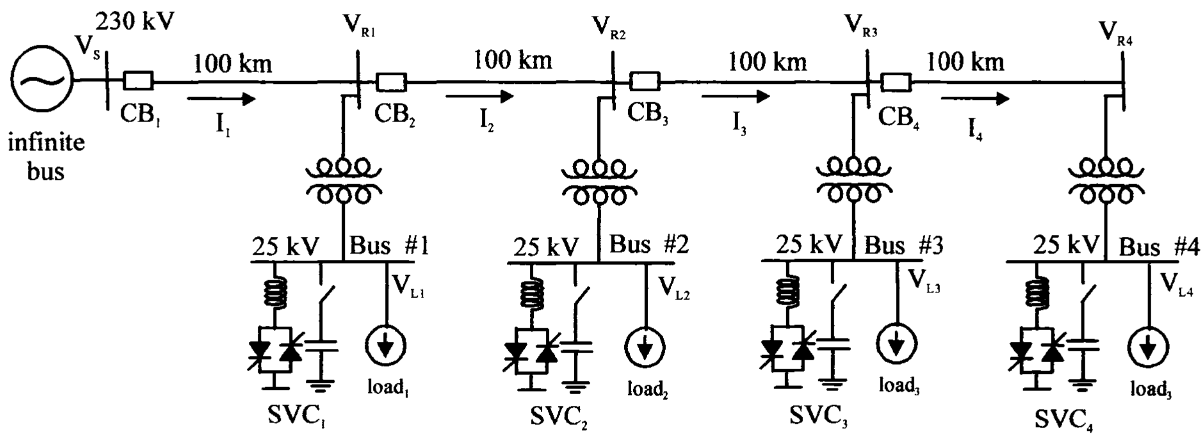

Figure 74 Case-Study of Radial line supported by SVCs connected to distribution buses

7.4.1.1 Steady-State Operation

Steady-state solutions have been obtained by 3 independent methods: (1) standard load flow studies; (2) phasor solutions of network equations using Kirchhoff's Voltage and Current Laws formulation; (3) simulation studies until the transients are damped out leaving the steady-state solutions. The solutions from the three independent methods agree.

The voltage phasors of $\mathbf{V_{Ri}}$ and $\mathbf{V_{Li}}$ are plotted in Fig. 75 The distribution voltage phasors $\mathbf{V_{Li}}$, i=1,2..4, lie on the unit circle, whereas the magnitudes of transmission bus phasors $\mathbf{V_{R1}}$ to $\mathbf{V_{R4}}$ are 0.91, 0.92, 0.96 and 0.98 pu respectively. The large angle on the sending end side and the crowding at the end reflect the fact that the line sections of currents $\mathbf{I_1}$, $\mathbf{I_2}$, $\mathbf{I_3}$ and $\mathbf{I_4}$ in Fig.6 carry powers of 800 MW, 600 MW, 400 MW and 200 MW, respectively.

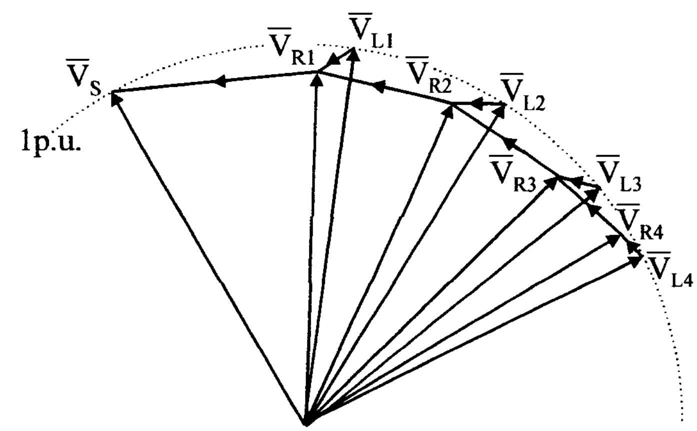

Figure 75 Steady-State Voltage Phasors

7.4.1.2 Comparisons of Two VS Schemes

The 2nd and 4th columns of Table V summarize the reactive powers $\mathbf{Q_{iD}}$ of the SVCs and the complex powers $|\mathbf{S_{iD}}|$ of the transformers at each node when VS is provided on the distribution buses. The quantities are per unitized to the surge impedance loading of the 230 kV line (P_{SIL}=211 MW).

The total requirements in Mvar and MVA are listed in the last row. For comparison, the reactive powers $\mathbf{Q_{iHV}}$ and the complex powers $|\mathbf{S_{iHV}}|$ of the transformers for SVCs on the transmission buses are listed in the 3rd and 5th columns. From the bottom row, one sees the savings coming from the step-up transformers in the first 3 nodes. The reduction of Q

(603-494) Mvar looks small but in terms of dollars capacitive Mvar is more costly than transformer MVA. The numbers in Table V do not include the requirements of (N-1) reliability.

Table V

High Voltage Bus vs Distribution bus for the test system from Fig.74

node i	Q_{iD} reactive power	Q_{iHV} reactive power	$\lvert S_{iD} \rvert$ transfor mer	$\lvert S_{iHV} \rvert$ transfor mer
1	0.904 pu	1.515 pu	1.311 pu	2.465 pu
2	0.756 pu	0.818 pu	1.214 pu	1.768 pu
3	0.429 pu	0.529 pu	1.042 pu	1.479 pu
4	0.251 pu	NIL	0.983 pu	0.95 pu
Σ	2.341 pu	2.862 pu	4.549	6.662 pu
Σ	494 Mvar	603 Mvar	959 MVA	1405 MVA

7.4.1.3 Comparison of Transmission Line Losses

As $\lvert \mathbf{V_{Ri}} \rvert < 1.0$ for every node in Fig. 75, it is expected that the current $\mathbf{I_i}$ in every transmission line section is higher than for the case of transmission bus VS which regulates the node voltage at $\mathbf{V_{Ri}}=1.0$. As transmission line power loss is proportional to $\lvert \mathbf{I_i} \rvert^2$, the power loss is expected to be higher for distribution bus VS than transmission bus VS. Fig. 76 plots the ratio of total transmission power loss (distribution bus VS)/(transmission bus VS) as a function of the real power loading at every bus.

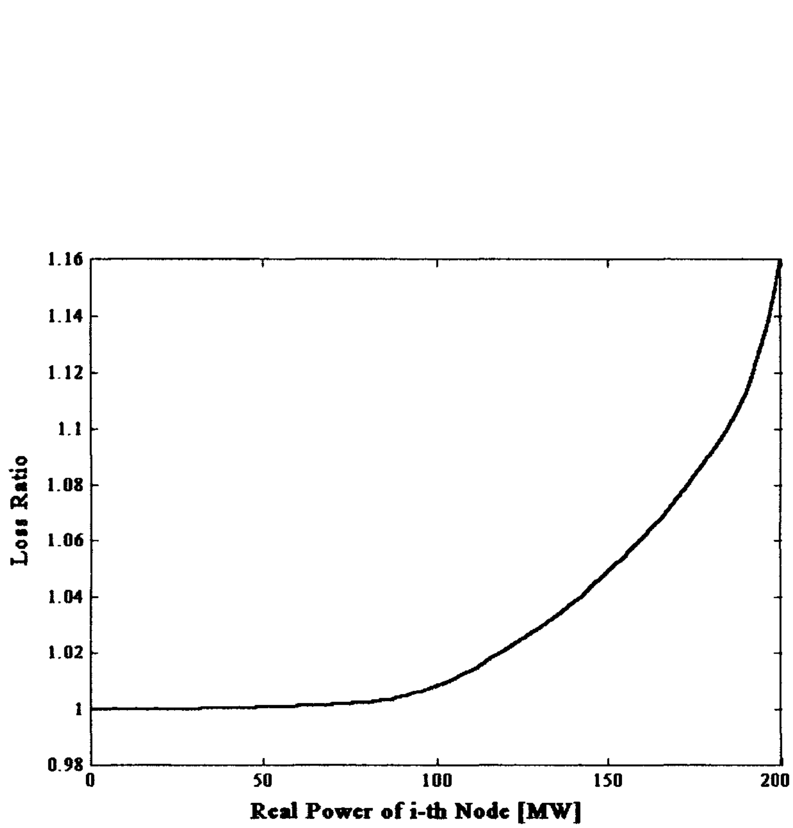

Figure 76 Ratio (distribution bus VS)/(transmission bus VS) of Transmission Line Losses

Up to 100 MW, the difference is negligible. At the peak loading of 200 MW, the increase is only around 16%. From the cost viewpoint, it is the difference in energy loss (time integral of power) which is significant. The peak load occurs only for a small fraction of the time.

7.4.1.4 Comparison of the Cost

The comparison of cost is shown in Table VI. The 2nd and 5th columns list the inductive Mvar/ capacitive Mvar requirements of the 4 nodes for distribution and transmission bus compensation respectively. The cost of thyristor switching is estimated as \$40/kVAR on the distribution level and 50 \$/kVAR at transmission level. The difference in the cost is due to the transformer that is assumed to be 20% of equipment cost [19]. Thus, the entry for node 1 under $\mathbf{Q_{iD}}$ SVC is \$10.5million=\$40x(65+195)x10^3. For comparison the same cost for high voltage bus compensation under $\mathbf{Q_{iHV}}$ is \$22m.

Table VI

Cost Estimate (SVC consisting of TCR -TSC)

node i	Q_{iD} [Mvar]	Q_{iD} [$ million]		Q_{iHV} [Mvar]	Q_{iHV} [$ million]	
		SVC	N-1		SVC	N-1
1	-65/+195	10.5	3.5	-110/+330	22	22
2	-55/+160	8.6	2.87	-60/+180	12	12
3	-30/+90	4.8	1.6	-40/+120	8	8
4	-20/+60	3.2	1.1	NIL	NIL	NIL
Σ	-170 +505	27	9	-210 +630	42	42

The 4th and 7th columns list the cost of providing (N-1) reliability. As shown in Fig. 32, each node is served by 4 SVCs. The $3.5m represents $10.5/(N-1) where N=4. Applying the (N-1) reliability practice, the authors have used N=2 for transmission voltage bus compensation. The $22m comes from $22m/(N-1) where N=2. From the bottom lines of the tables, the cost savings are $36m=$(42+42-27-9)m. Estimation figures such as $40/kvar and $50/kvar include the cost of transformers and auxiliary equipment so that the transformer savings listed in Table V become lost in this rough estimation practice. In addition, the savings in not having to use tap changers for distribution voltage regulation have not been factored in.

7.5 Fault Studies

It is necessary to show that the system of Fig.74 can survive a three-phase-to ground fault and on clearing the fault, the system is able to return to the steady-state solution that existed prior to the occurrence of the fault. Such studies are conducted using digital simulations.

7,5.1 Model of Static Var Compensator (SVC)

The distribution VS in each distribution voltage bus in Fig. 74 consists of a Thyristor Controlled Reactor - Thyristor Switched Capacitors (TCR-TSC) and switched/fixed capacitors. The capacitors are Y connected, with the neutral solidly grounded. The total amount of fixed/switched capacitors is: 500 Mvar at bus #1, 250 Mvar at the bus #2, 200 Mvar at bus #3 and 150 Mvar at bus #4. The TCRs provide for dynamic voltage control. They are delta connected. Fixed capacitors are tuned to filter out the 5th and 7th harmonics of the TCR. The simulations made use of the default model of the SVC of HYPERSIM. A description of the model is given in [72].

7.5.2 Load Models

A variety of load combinations have been studied but there is enough space in this chapter to present only one of them. This consists of a combination of:

(i) a resistive load to represent heating load

(ii) induction motor load representing industrial and/or agricultural load,

(iii) dynamic load model to represent combination of commercial and residential load

Detail descriptions of the load models are given in [72].

The dynamic load model represents reactive power and real power of the load at any instant of time as functions of voltage level according to (7.1) and (7.2) [73,74]

$$P = P_0\left(\frac{V}{V_0}\right)^{np}\left[\frac{1 + T_{P1}S}{1 + T_{P2}S}\right] \tag{7.1}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{nq}\left[\frac{1 + T_{Q1}S}{1 + T_{Q2}S}\right] \tag{7.2}$$

where P_0 and Q_0 are respectively the nominal active and reactive power, V_0 is nominal voltage and *np* and *nq* are variation coefficients of active end reactive power as a function of the voltage. The model is valid only for fundamental frequency between 50 and 70 Hz and for voltage level greater than 0.7 p.u. If the voltage drops below 0.7 p.u., the model behaves as constant impedance. Detailed model description is given in [72].

7.5.3 Transmission Line Model

In Fig. 70 and 72, the transmission line sections have been represented by inductive reactances jX_i, i=1,2,..N. Since the model based on the more accurate telegraph equations is available in the simulation software, it is used in the simulations. The data of the distributed parameter model are:

z, impedance per km (z = 0.3 ohm/km)

y, admittance per km ($y = 5\text{x}10^{-6}$ S/km)

r, resistance per km (r = 0.04 ohm/km)

Based on the distributed model, the characteristic impedance of the line is $Z_S = \sqrt{z / y} = 250\, ohms$ and the Surge Impedance Loading (SIL) of the line $P_{SIL} = \dfrac{|\overline{V}_S|^2}{Z_S}$ is 211 MW. The line in use is single circuit consisting of two bundled conductors.

7.5.4 Simulation Results

7.5.4.1 Three Phase to Ground Fault

The simulation test consists of introducing a three-phase-to-ground fault in any portion of the transmission line. The composition of the load at Nodes #2 to #4 is: (i) Resistive

Load-- 30% , (ii) Induction Motor Load--35 %., (iii) Dynamic Load--35%. Load parameters are taken from [1]. To reflect the fact that industries are nearer to generation sources, the composition of the load at Node #1 is: (i) Resistive Load-- 20% , (ii) Induction Motor Load--65 %., (iii) Dynamic Load--15%.

The objectives of the simulations are: (i) to be assured that the local controls of the distributed SVCs operate harmoniously in the restoration; (ii) to ascertain that there is no voltage instability due to induction motors dynamics following the clearance of the fault [75,76].

Upon detection of the three-phase-to-ground fault, the "upstream" circuit breaker CB opens within 100 ms. Because of the great amount of fixed/switched capacitors connected across the induction motor loads, the minimum re-closing time to allow for cooling of the plasma to avoid re-striking based on the formula:

$$t = 10.5 + \frac{kV}{34.5} cycle \tag{7.3}$$

has been found to be insufficient. The formula is taken from [77]. By monitoring and waiting for the fault currents to fall to zero, the safe re-closing time is found to be 550 ms.

7.5.4.2 Results

The three-phase-to-ground fault is assumed to occur in the first transmission line section, between $\mathbf{V_S}$ and $\mathbf{V_{R1}}$ in Fig. 74. The fault is triggered at 2.1 s in Fig. 77 -80. The Circuit Breaker CB_1 opens the line at 2.16 s. All the four load centers lose the ac voltage supply V_S immediately. The Circuit Breaker re-closes in 2.71 s to allow for the 550 ms safe re-closing time. Some of the simulation results are shown in Fig.77 to 80.

Fig.77 is a record of the distribution bus voltages. Although Circuit Breaker CB_1 is open for 550 ms after the fault, the distribution bus voltages do not drop to zero immediately because of the self-excitation between the compensation capacitors and the induction motors. Upon re-closing of Circuit Breaker CB_1, the bus voltages recover, the recovery time being slowest at the remote #4 bus.

Fig. 78 shows the rms current of each load center. This current is the sum of the currents from the resistive load, the induction motor load and the dynamic load.

Fig. 79 shows the induction motor component of the load current. The large over-currents are not sources of concern because the current protection would have tripped the induction motors if their safe heating limits have been exceeded. The tripping would speed the voltage recovery.

The motor speeds in Fig. 80 are records of the deceleration upon the opening of Circuit Breaker CB_1 and the acceleration following the re-closing of CB_1. Since node #4 is separated from the infinite bus by the largest line impedance, its voltage takes the longest to recover as shown in Fig. 77. As a result, as shown in Fig. 80, the induction motor of #4 bus takes the longest time to recover rated speed.

The tests are conducted to simulate the worst case scenario when all the induction motors do not have under-voltage protection. This test shows that there is no voltage collapse and voltage recovery is accomplished by the SVCs on the distribution buses operating, harmoniously without conflict, under local control.

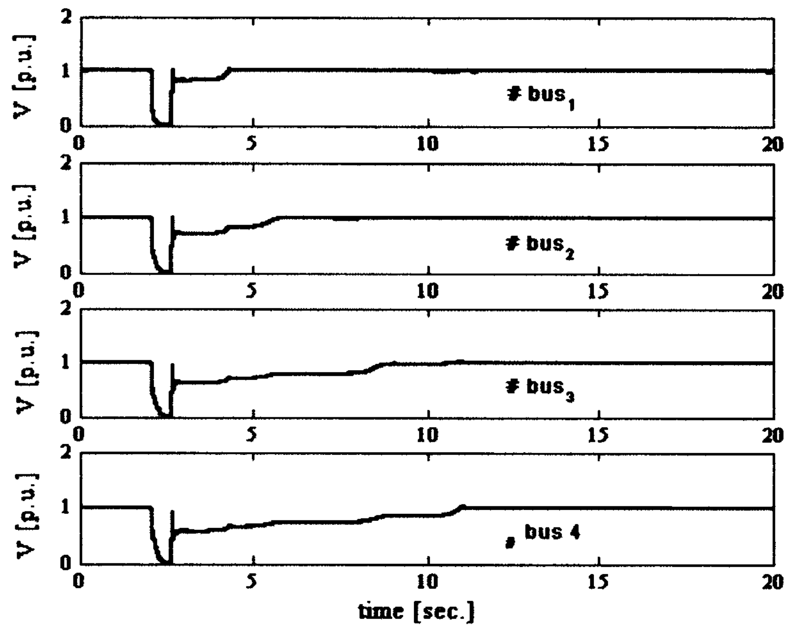

Figure 77 Load Bus Voltages (RMS) at Load Centers

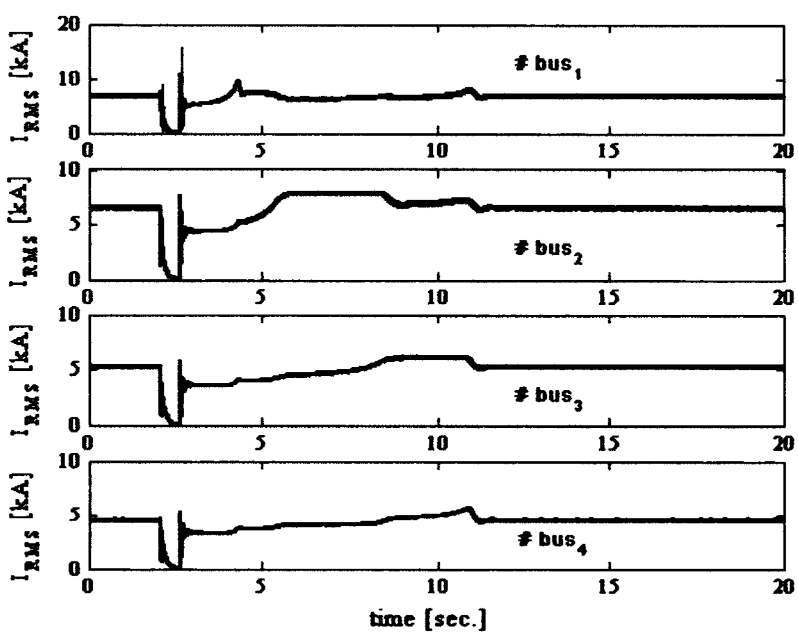

Figure 78 Currents (RMS) to the load centers

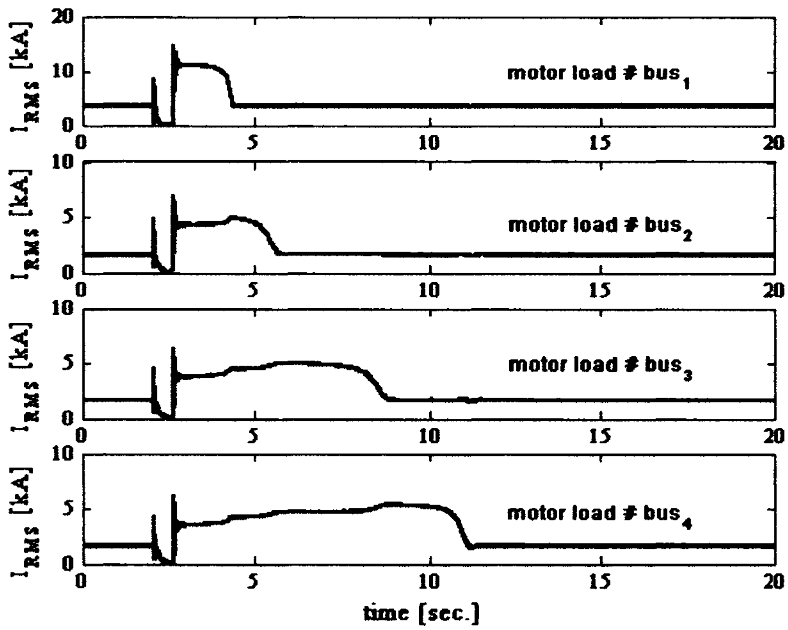

Figure 79 Currents (RMS) drawn by induction motors.

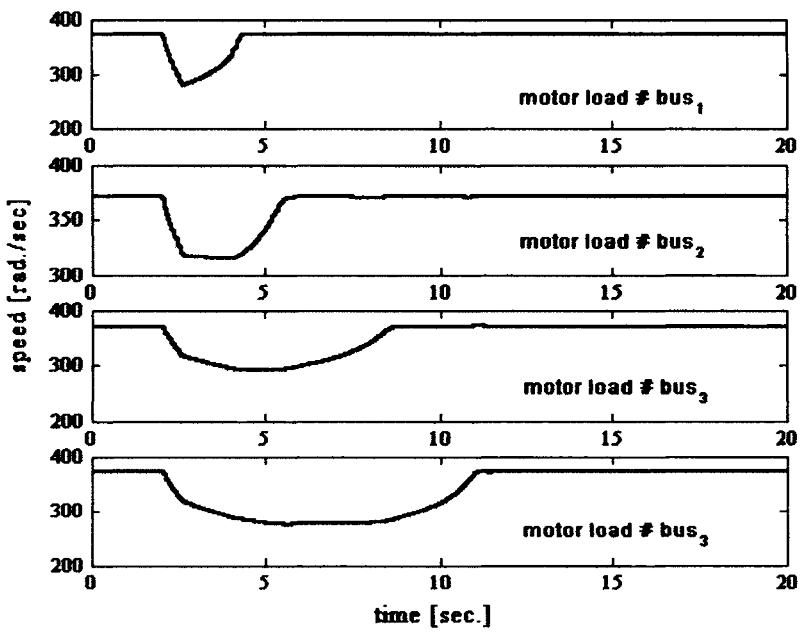

Figure 80 Speeds of Induction Motors at Load Centers. The motors slow down during fault and accelerate after fault clearing and line reclosing. Reclosing time used is 550 ms

7.5.4.3 Requirement of Longer Re-Closing Time

As capacitors, which provide voltage support, can self- excite the induction motors to feed the fault currents, a longer re-closing time has been found to be necessary. Otherwise, the system survives the short circuit fault.

7.6. Conclusion

This chapter has demonstrated that voltage support of a long transmission line, with load centers spaced along the line, can be provided on the distribution buses. The radial line has been chosen to demonstrate the concept because the radial system gives a clear insight into the proposed approach. It should be possible to extend the concept to mesh networks but more studies are required to confirm this. The benefits emerging from the proposed concept over the traditional voltage support at the transmission buses are: i) elimination of the step-up transformer for coupling the VS system to the transmission buses, ii) lower var requirements iii) lower cost in providing (N-1) reliability and iv) elimination of LTC transformers for distribution voltages regulation.

As voltage support on the distribution buses is a valuable alternative to traditional voltage support at the transmission buses, it offers distribution system engineers the opportunity to provide voltage support of transmission systems as ancillary service.

As some utilities rely on intentional, distribution voltage reductions during emergencies to obtain load reduction and transmission system relief, the proposed concept can lead to potential conflict between transmission and distribution system requirements. In this case, proper coordination of control would be required.