CHAPTER V

EFFECTIVENESS OF SERIES & SHUNT COMPENSATION ON MULTI-PHASE TRANSMISSION LINES

CHAPTER 5

EFFECTIVENESS OF SERIES & SHUNT COMPENSATION ON MULTI-PHASE LINES

5.1 INTRODUCTION:-

The stability requirement limits the permissible power on EHV lines, which decreases with increasing line length. The use of series capacitors in long distance transmission lines offers an effective and economical means of improving stability limits and permits the line to carry more power.

The amount of series capacitance used in the line is usually referred by the degree of series compensation (S), which is defined as the ratio of the capacitive reactance of the series capacitor to that of the total series inductive reactance of the line. But the net reactance, preferably called the transfer reactance, is not just the arithmetical difference between the total inductive reactance of the line and the capacitive reactance of the series capacitor. The net transfer reactance not only varies with the degree of series compensation used, but also depends upon its location along the line, the line length and the number of banks over which the series compensation is distributed. In other words, the net transfer reactance depends both on the degree of series compensation and its 'effectiveness'. A index termed 'Compensation Efficiency' has been introduced in this chapter so as to give a clear representation for the effectiveness of a given quantum of series compensation.

The use of shunt reactors on EHV lines and their advantages in improving the system performance are well known. The presence of shunt reactor on a series compensated line modifies its performance in a rather different way. It is shown that the shunt reactor not only helps in holding down the voltages, but also increases the effectiveness of the series capacitor.

Further, the use of shunt reactors on series compensated lines modifies the performance in different ways depending on the degree of shunt compensation. An advantage from the point of view of stability can be realised only if the degree of shunt compensation chosen is above a 'critical value'. This critical value of shunt compensation depends on the degree of series compensation, the length of the line and the location of the compensating units. The critical value of shunt compensation required below a certain degree of series compensation may not be practicable.

The chapter presents a detailed analysis of a series compensated line in terms of the '**Compensation Efficiency**' index. Expressions are derived for the compensation efficiency for different possible cases and also for the critical shunt compensation.

5.2 LINE CONSTANTS AND ASSUMPTIONS:-

The analysis is carried out on a typical 400 KV line of different lengths, having the following constants.

Line length : 400 to 1000 Kms.

Operating Voltage : 400 KV

Type of conductor: Twin mouse

Bundle spacing : 25 Cms.

Phase spacing :As shown in Fig.2.3

Height of the lowest Conductor from ground : 21.9 M.

Shield wires : Two 0.548 Aluminium-clad steel (r_c = 0.7538 Ω /Km at 20^{0}c)

Earth conductivity: 0.01 mho /m

Computed line parameters per Km. for 3-ph Double Circuit:

L= 0.0005014 C= 2.43 E -8

Computed line parameters per Km. for 6-ph conversion of the same configuration:

L= 0.001268 C= 9.01 E -9

- Terminal equipments and machine variants are not considered.
- Shunt compensation is specified as susceptance.

An analysis is carried out in terms of the general line constants (ABCD constants) so as to realise an accurate representation of the system, and the computations are based on the following assumptions.

(a) Since the analysis is mainly for determining the effect and influence of shunt and series compensation on the line performance, the terminal equipments and the machine variants are not considered.

(b) Under normal operating load condition, the receiving end and the sending end voltages are taken as constants as 100% and 105%, respectively.

(c) For the purpose of satisfactory transient stability performance, the angular difference between the sending end and the receiving end voltage vectors is assumed to be 30 degrees.

(d) In this analysis, the shunt compensation is specified as susceptance of shunt reactor in per unit instead of MVAR, as it is felt that the susceptance will give a better circuit representation than its corresponding MVAR rating.

5.3 PRINCIPLE OF SERIES COMPENSATION :-

The fundamental principle involved in the application of series capacitors is the compensation of inductive line reactance by the introduction of capacitive reactance in series with line at theoretical steady state stability limit (neglecting the terminal equipment reactances). In such a case, the maximum receiving end power is given by

$$Pr_{max} = [\ |E_s\ E_r| \ /\ |B_0|\ ] - [\ |Er^2|\ |\ A_0| \ /\ |B_0|\ ] \cos (\ \beta_0 - \alpha_0) \qquad (5.1)$$

If the line resistance is neglected, the equation (5.1) reduces to

$$Pr_{max} = [\ |E_s\ E_r| / |B_0|\ ] - |E_s\ E_r| / X_L \tag{5.2}$$

Thus, any improvement which would offset the inherent reactance of the line (and of transformers) would mean a definite gain in the maximum power that can be transmitted. Hence, the partial or complete neutralization of the line and transformer reactances by the application of series capacitors, presents a convenient method by which an increase in the stability limit can be realised. Stability as well as economic and over-voltage conditions control the quantum of capacitive reactance that can be adopted in any particular case, and this quantum is normally referred to by the term "Degree of Series Compensation".

5.4 EFFECT OF LOCATION OF SERIES CAPACITORS :-

The position of the series capacitor bank is an important consideration in the case of long transmission lines where line charging plays an important role. The location of capacitor bank affects the fault currents, voltages seen by protective devices, stability limit and also the maximum power frequency over-voltage. Three important locations for the capacitor bank normally considered are,

(A) Sending end

(B) Mid-point of the line

(C) Receiving end.

For a loss-less line, the best location for the series capacitor from stability point of view can be mathematically proved to be at the centre of the line (Appendix A). The various effects of series compensation and its location can be best studied by the general line constants.

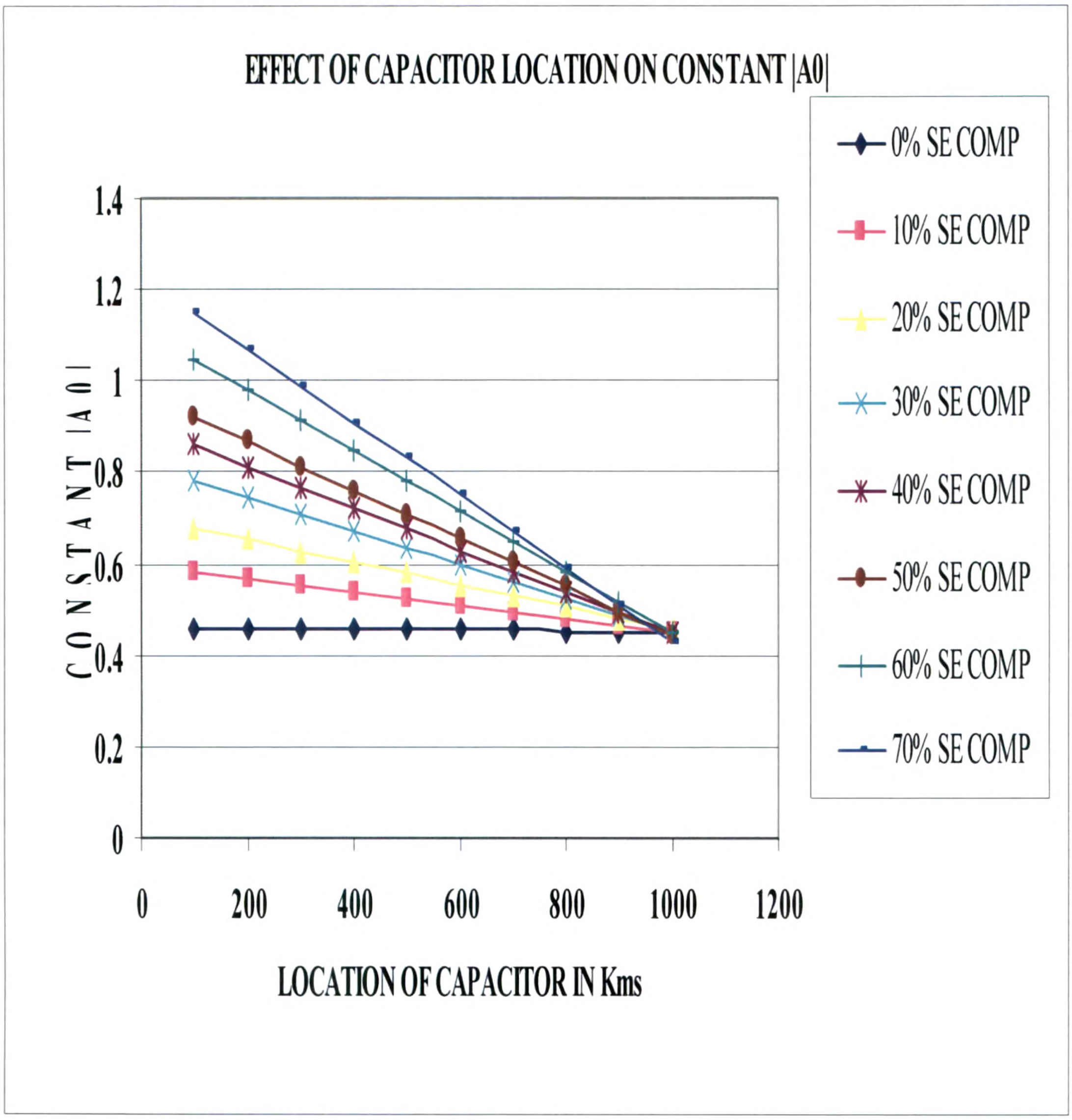


Fig. 5.1 Effect of Capacitor Location on Constant $|A_0|$

Fig.5.1 shows the variation of the constant A_0 for the series compensated line for different positions of the compensating bank. It is seen that for locations other than the receiving end, the magnitude of A_0 increases linearly with the degree of compensation. For minimizing power frequency over-voltages during light loads, a high value of A_0, very nearly equal to unity, is desirable. For the system considered, the magnitude of constant A_0 for the uncompensated line is 0.48, whereas for 70 percent series compensated line the value of A_0 increases to 1.10.

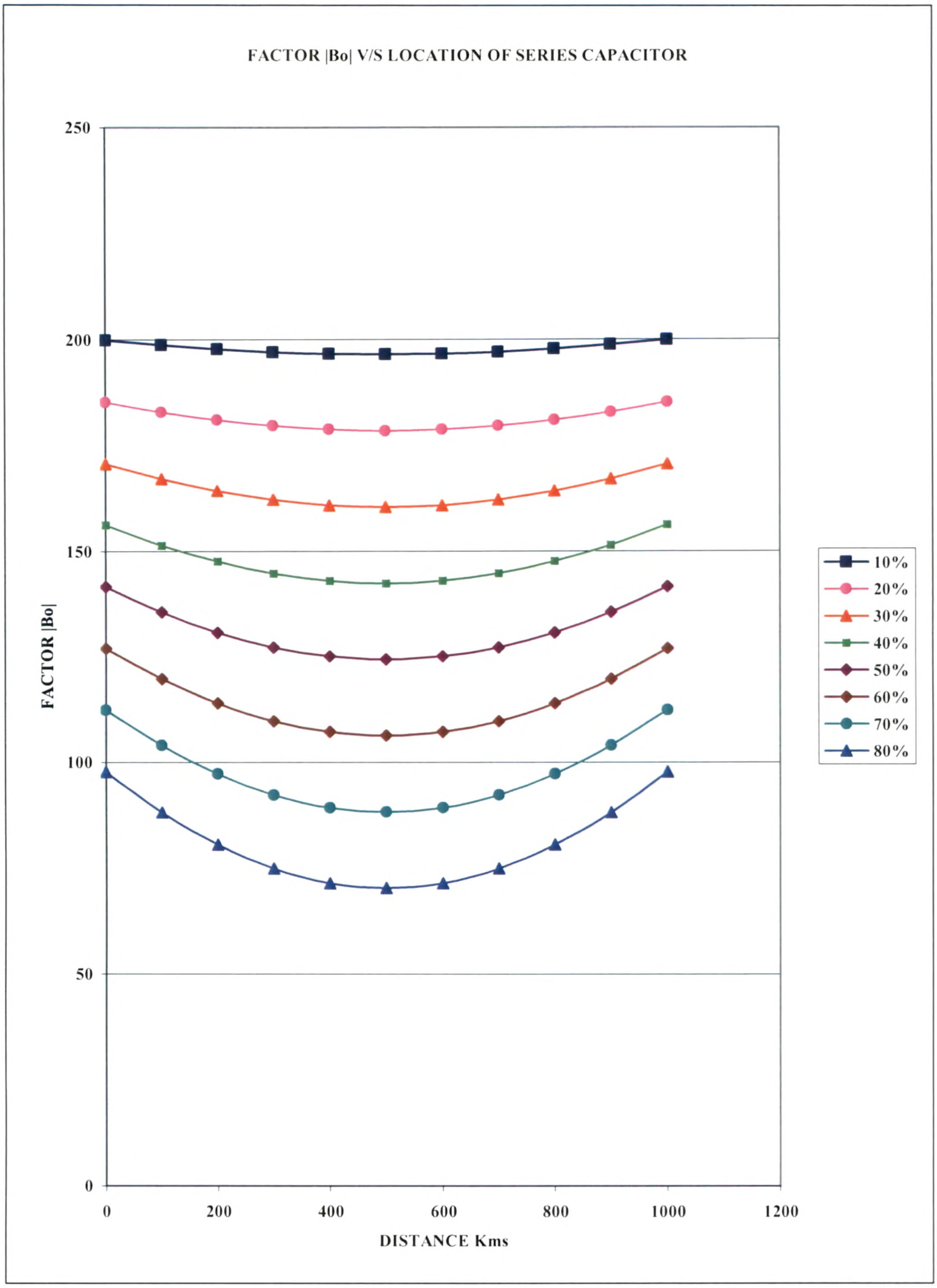


Fig. 5.2(a) Effect of Capacitor Location on Constant $|B_0|$

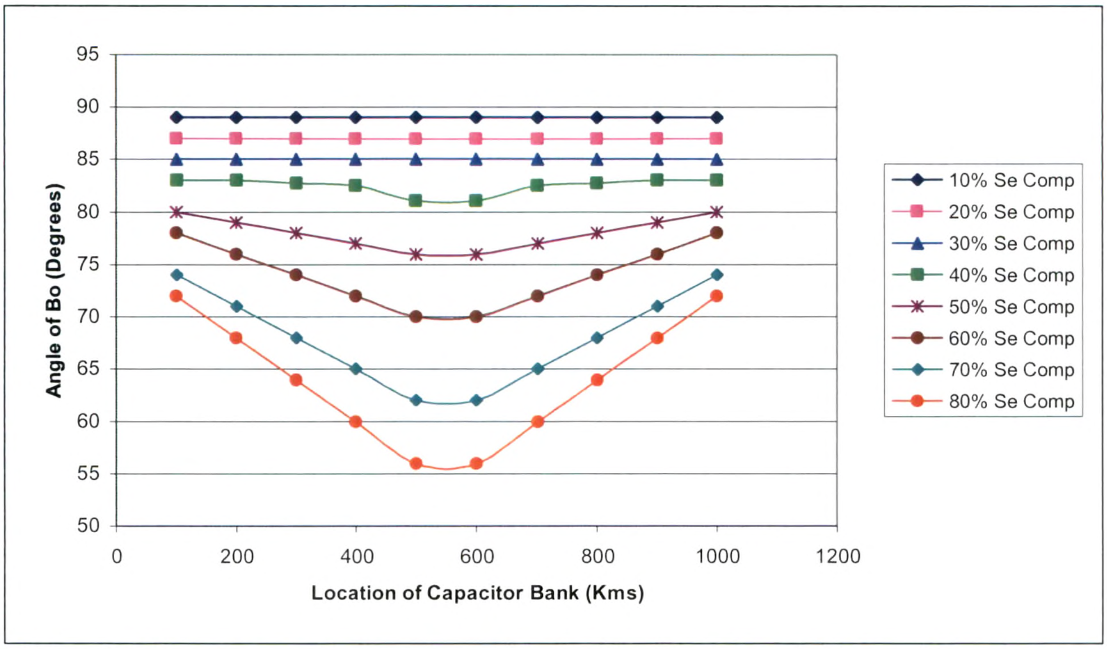


Fig. 5.2(b) Effect of Capacitor Location on Angle of Constant $|B_0|$

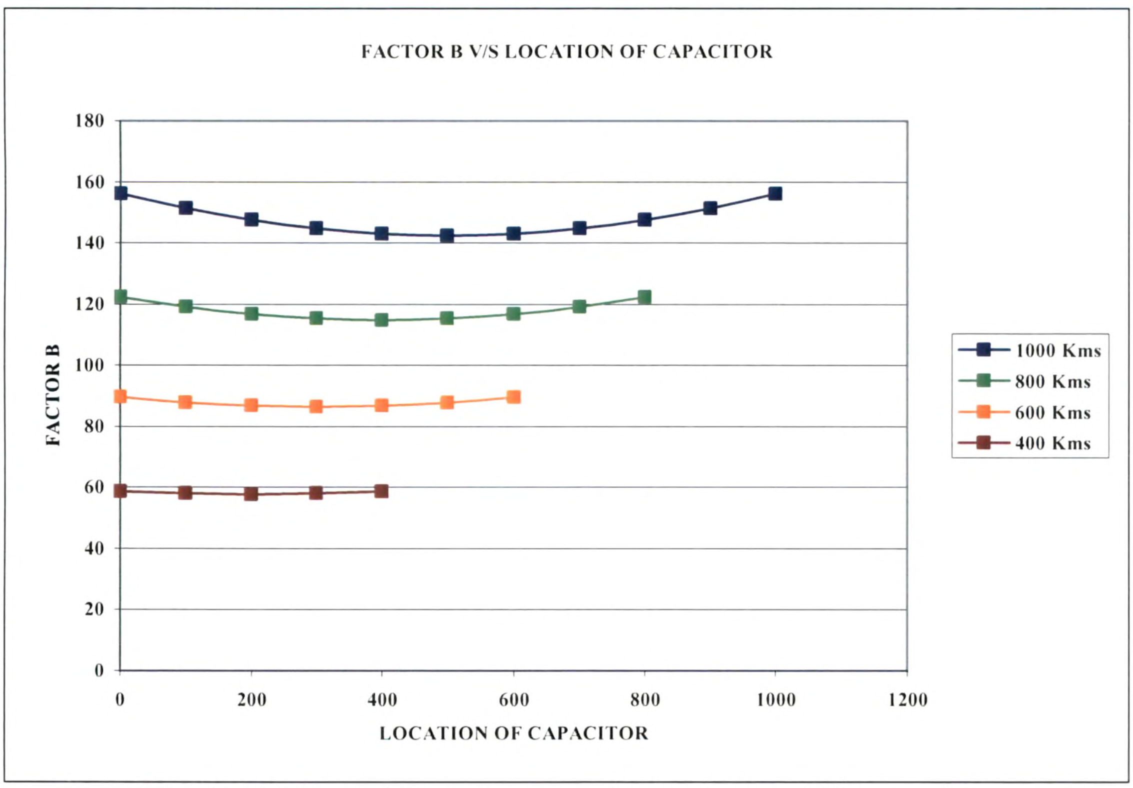


Fig. 5.2(c) Effect of Capacitor Location on Angle of Constant $|B_0|$ for the 40% Series Compensated Line

Figure 5.2(a) shows the variation of the constant B_0, the transfer impedance, which determines the power transfer capability of the line. The transfer impedance is minimum when the series capacitor is located at the centre of the line. It is seen from the fig.5.2 (a) for a normal compensation of 50 percent, the transfer impedance is about 20 percent less when the capacitor is placed at the centre than when placed at either ends.

Figure 5.2(b) shows a similar change in the line angle which is equivalent to the load angle at the steady state stability limit. Hence, from the view point of power transfer and power frequency over-voltages at no-load, the centre position for the capacitor bank yields maximum benefit.

Figure 5.2 (c) shows the effect of variation of capacitor location on transfer impedance B_0 for the 40% compensated line having different line lengths.

5.5 COMPENSATION EFFICIENCY:-

The stability limit of a series compensated line, neglecting the effect of line resistance and line charging, can be written as

$$Pr_{max} = E_s E_r / [X_L - X_C] \qquad (5.3)$$

Here, the net transfer impedance of the compensated line is taken as the algebraic difference of the inductive reactance and capacitive reactance. This assumption is correct in so far as short lines are concerned. But for longer lines, the resultant transfer reactance will be more than the value of the arithmetical difference between X_L and X_C due to the line charging effect. In order to account for this discrepancy, the term **"Compensation Efficiency"** is introduced which indicates the effectiveness of the series capacitor bank in reducing the transfer impedance of the line.

The Compensation Efficiency (K) is defined as the ratio of the net reduction of transfer reactance to the reactance of the series capacitor used. Thus the effective series reactance X_C' (as compared to the actual value X_C) is given by

$$X_C' = K X_C \tag{5.4}$$

And the maximum power transfer over the line can be calculated from equation 5.5

$$Pr_{(max)} = E_s E_r / [X_L - X_C']$$

$$= E_s E_r / X_L [1-SK] \tag{5.5}$$

Where, X_L is the transfer reactance of the line. The compensation efficiency is usually less than 100 percent, but under certain conditions it can be more than this value. A high value for K is desirable for realising a high stability limit.

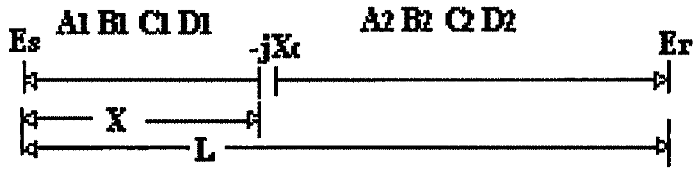
5.5.1. EXPRESSIONS FOR COMPENSATION EFFICIENCY:-

When a series capacitor is placed at a distance X from the sending end of the transmission line, as shown in figure 5.3(a), the effective transfer impedance is given by

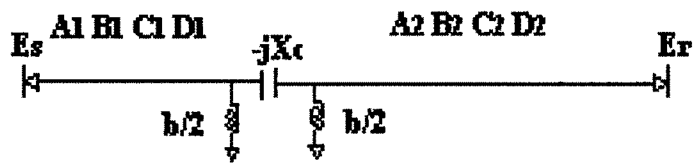
$$B_0 = A_1B_2 + B_1D_2 - j\, A_1D_2X_C \tag{5.6}$$

This expression shows that even though a series capacitor having reactance X_C is used, the net reduction in the transfer impedance is only $A_1D_2X_C$. Hence the coefficient of X_C in this expression for B_0 must represent the effectiveness of series compensation. Since the compensation efficiency is defined as the ratio of the reactances only, it is given by,

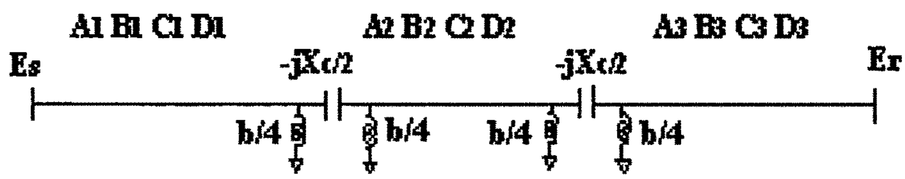
$$K = \mathrm{Re}\,(A_1D_2) \tag{5.7}$$



(a) Single CapacitorBank



(b) Single Capacitor Bank With ShuntReactor



(c) Two Capacitor Banks With Shunt Reactors

Fig. 5.3(a, b and c) Schematic Capacitor Location and Shunt Compensation

The curves in figure 5.4 show the variation in compensation efficiency for a single capacitor bank for different line lengths. The capacitor will be most effective when placed at the mid point of the line irrespective of the line length. The compensation efficiency of a single capacitor bank is dependent on the line length and the location of the capacitor, but is independent of the degree of series compensation. In addition, the effectiveness of a given degree of series compensation decreases with the increasing line length, which means that a given degree of series compensation results in lesser improvement in stability limit for longer lines.

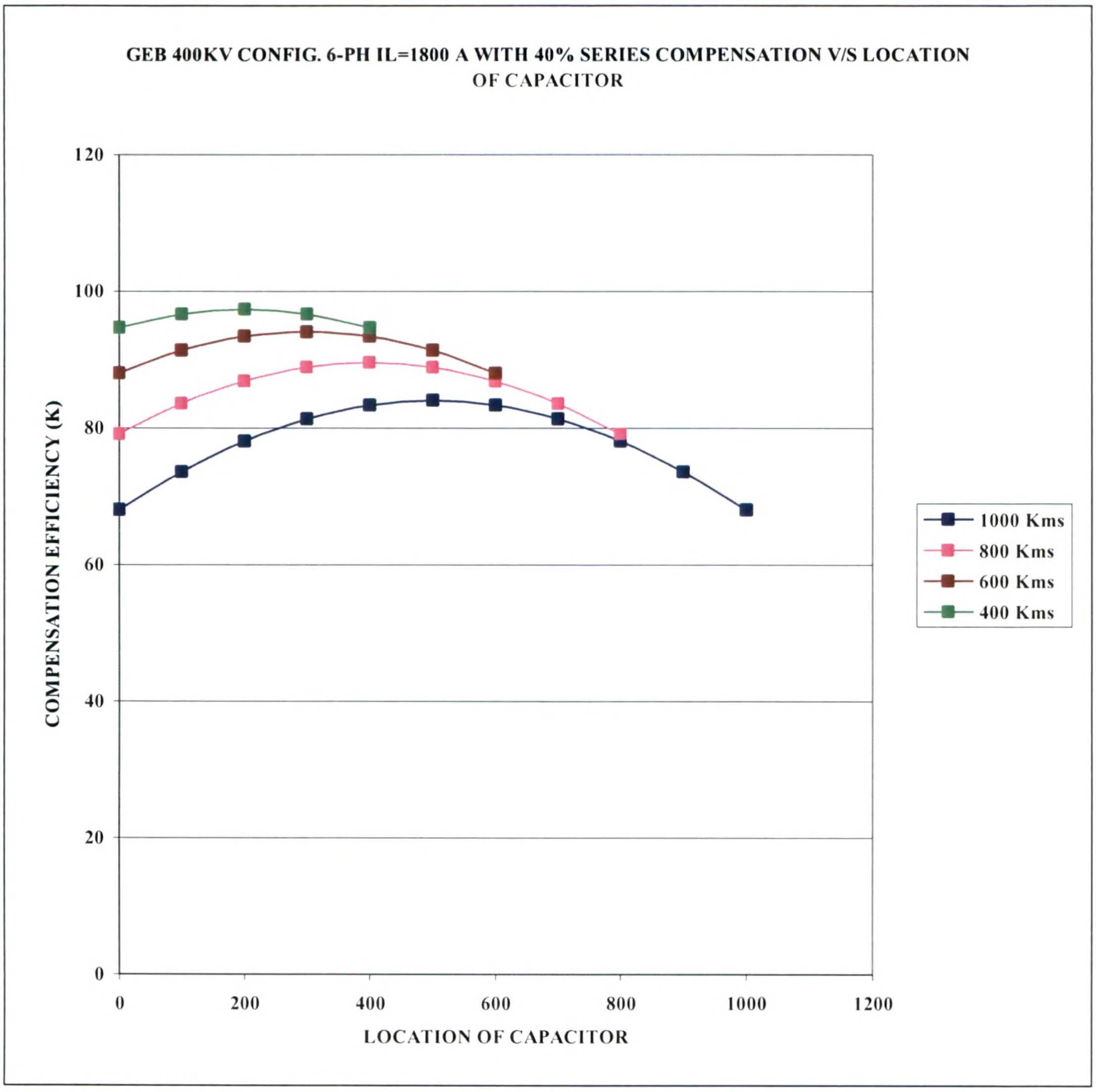


Fig. 5.4 Effect of Capacitor Location and Line Length on Compensation Efficiency when Single Capacitor Bank Used.

The constraint of maximum permissible voltage across the capacitor during fault conditions and overloads necessitates the provision of splitting the compensation and providing banks at a number of places along the line. When two equal capacitor banks are placed at one third points along the line, the compensation efficiency is given by equation 5.8, and in such cases, the compensation efficiency will be a function of the degree of series compensation also, in addition to the line length and the location.

$$K = \mathrm{Re}\,(A^3 + ABC - j\,A^2CXc/4) \qquad (5.8)$$

Where A, B and C are the general line constants for one third line length (Appendix A). Similarly, equation (5.9) gives the compensation efficiency when three capacitor banks are located at quarter point along the line.

$$K = \mathrm{Re}\,[(A^2 + BC - j\,ACXc/3)\,(3A^2 + BC - j\,ACX_C / 4) + 4\,A^2BC]\,/3 \qquad (5.9)$$

Where A, B and C are the general line constants for one-fourth line length. The above equations show that the compensation efficiency varies with the degree of series compensation also. For example, the compensation efficiency for two capacitor banks is found to vary from 72 to 82 percent for a change of 10 to 80 percent in the degree of series compensation respectively. However it has been found that at low degrees of series compensation the compensating efficiency with two capacitor banks is slightly less than that obtained with a single capacitor bank. This is, in fact, the reason for the requirement of higher MVAR rating for two capacitor banks at one-third points than for one capacitor bank at mid-point [133].

5.5.2. INFLUENCE OF SHUNT COMPENSATION:-

Shunt compensation is an effective means of reducing the power frequency over-voltage and surges both during faults and switching operations. The degree of shunt compensation required for limiting the over-voltages and preventing self-excitation of generators, is found to vary considerably with the degree of series compensation and its location. In addition, when properly located, the shunt reactor is found to influence the power capability of the line. This can however be explained in terms of compensation efficiency. If the shunt reactor series capacitor combination is located at a distance x from the sending end of the line, as shown in figure 5.3(b), then the effective transfer impedance is given by equation (5.10), and the corresponding compensation efficiency by equation (5.11) (Appendix A)

$$B_0 = A_1B_2 + B_1D_2 + - j\,B_1B_2 - j\,X_C\,(A_1 - jbB_1/2)(D_2 - jbB_2/2) \qquad (5.10)$$

$$K = \mathrm{Re}\,[\,(A_1 - jbB_1/2)(D_2 - jbB_2/2) + bB_1B_2/X_C] \qquad (5.11)$$

Where, "b" is the total susceptance of the shunt reactors used. The expression for the compensation efficiency reveals the influence of the shunt reactor on the effectiveness of the series capacitor. For a given location and degree of series compensation the compensation efficiency increases with the increase in shunt compensation, provided the shunt compensation is above a critical value b_{cr}. The critical shunt compensation is expressed in terms of the susceptance and the corresponding MVAR depends on the voltage level at the shunt reactor location. An expression for this critical shunt compensation can be obtained by equating the terms containing "b" in the expression on the right hand side of equation (5.11) to zero. However, the expression for b_{cr} becomes quite intricate, but simplifies itself considerably for the loss less line (equation 5.12).

$$b_{cr} = 4/X_C - 2\,[\,(A_1B_2+B_1D_2)/(B_1B_2)] \qquad (5.12)$$

For the series compensated line with the series capacitor bank housed at mid point, the compensation efficiency decreases with the increase in shunt compensation. It is, however, noticed that beyond the critical shunt compensation value, the compensation efficiency increases, and thereby the power transfer capability also increases. At a lower degree of series compensation, the shunt compensation required to improve the stability is too high to be practicable. This peculiar behaviour of shunt reactors on a series compensated line, plays an important role in the switching operations for the optimum control of power system transients. This aspect is discussed fully and the necessary modifications of the switching scheme are given in section (5.6).

The value of the critical shunt compensation (b_{cr}) is just the value of shunt compensation beyond which the transfer impedance of the line starts decreasing from the value corresponding to zero shunt compensation. This, however, cannot be called as an optimum compensation for the fact as illustrated in figure 5.5. The figure shows the nature of variation of the transfer impedance of a series compensated line with respect to shunt compensation on which the critical shunt compensation $\mathbf{b_{cr}}$ is marked. But there exists still another point of interest that may be called the **"optimum shunt compensation ($\mathbf{b_{opt}}$)."** It is at this point that the transfer impedance changes the direction of its variation. An expression for this optimum shunt compensation can be obtained by differentiating and equating the expression for the compensation efficiency to zero. This yields,

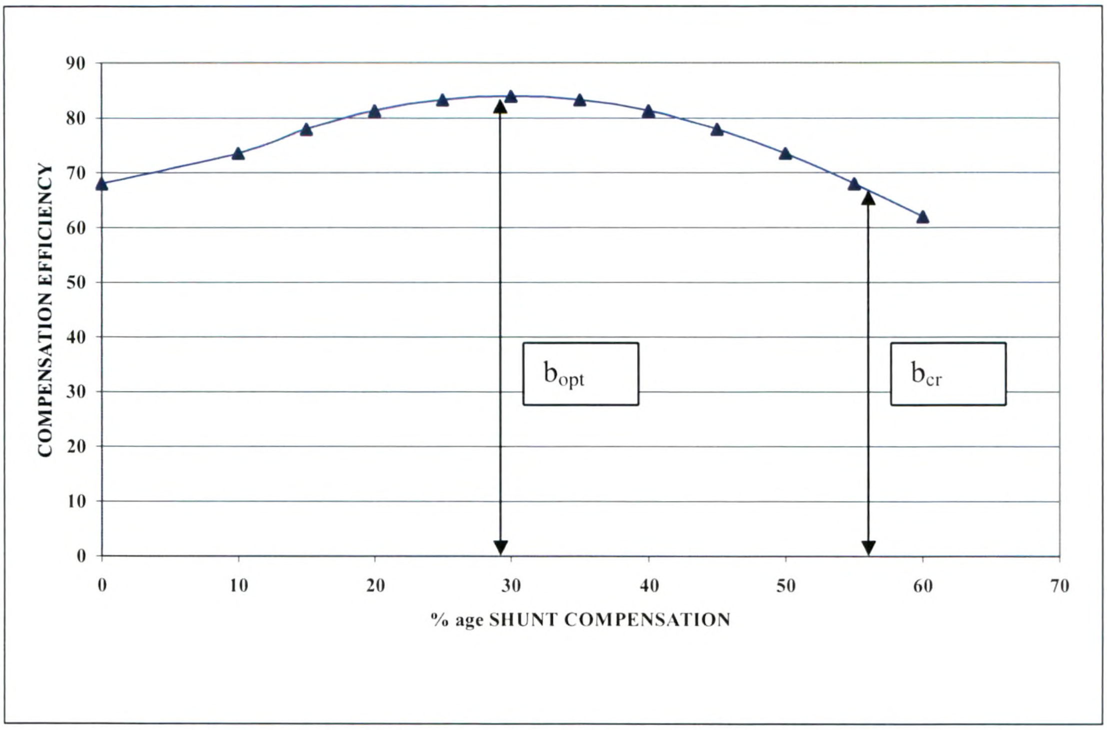


Fig. 5.5 Effect of Shunt Compensation on 40% Series compensated line

$b_{opt} = 2/X_C - [\,(A_1B_2+B_1D_2)/\,(\,B_1B_2)]$ (5.13)

And for this particular case we find that,

$b_{opt} = ½\ b_{cr}$

For gaining an advantage from the stability point of view, the shunt compensation must be above the value of $\mathbf{b_{cr}}$.

5.5.3. SINGLE CAPACITOR BANK:-

Several possible configurations of series and shunt compensation of a 1000 km transmission line were examined; and some of the important findings are presented here. The curves in fig. 5.6 show that the compensation efficiency decreases considerably with the increase in shunt compensation, when the capacitor bank is located in the vicinity of the mid point of the line. However, at higher values of series compensation the effect of shunt compensation tends to increase the compensation efficiency for all positions of the series capacitor bank.

5.5.4 POWER LIMITS:-

For the experimental line, the power limits, the efficiency of power transmission, the sending end power factors, the no-load input impedance of the line, the transfer impedances, the angle of steady state stability limit, the power frequency voltages across the capacitor during load, and the Ferranti over-voltage at the receiving end during light load conditions etc. were digitally computed for all combinations of series and shunt compensation.

The graphs are presented here to support the validity of the previous analysis in terms of the compensation efficiency. Figure 5.6 shows variation of the power capability of the line with respect to shunt compensation for different degrees of series compensation. Figure 5.7 gives the variation for the case when the series capacitor bank is at the mid point. The curves in figure 5.6 & 5.7 clearly show the detrimental effect of shunt compensation on the power transfer capability of the line at lower degrees of series compensation. These curves also indicate an advantage of shunt compensation on the power transfer capability at higher degrees of series compensation. The figure 5.6 and 5.7 show that the compensation will be far more effective when capacitor bank is placed at either ends of the line. Without shunt compensation, the power that can be transferred is about 1.0 p.u. with 60 percent series compensation with capacitor bank being at the mid point. If the series capacitor bank is located at the receiving end, power transfer decreases to about 0.7 per unit.

With a shunt compensation of 0.6 p.u. (Which limits, the Ferranti over voltage to 1.05) the corresponding figures are 1.11 and 1.17 p.u. respectively. This advantage increases very rapidly beyond these values of shunt and series compensation. Even though this figure 5.7 shows enormous advantage of compensation at the ends of the line, a final decision on the location must take into account factors such as self-excitation, switching surges, Ferranti over-voltages etc.

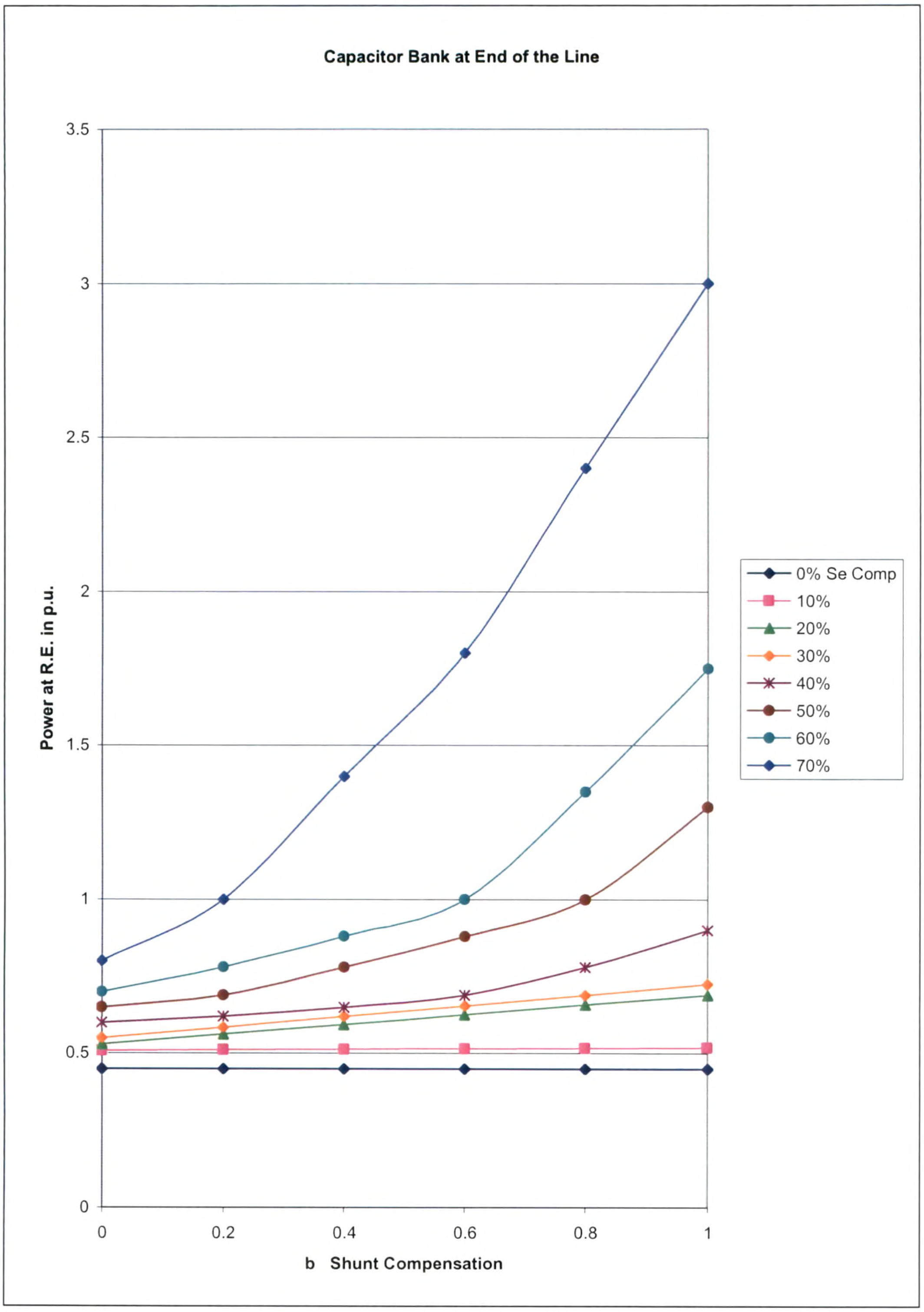


Fig. 5.6 Effect of Series and Shunt Compensation on Transmission Line Capacity, keeping Capacitor Bank at End of the Line

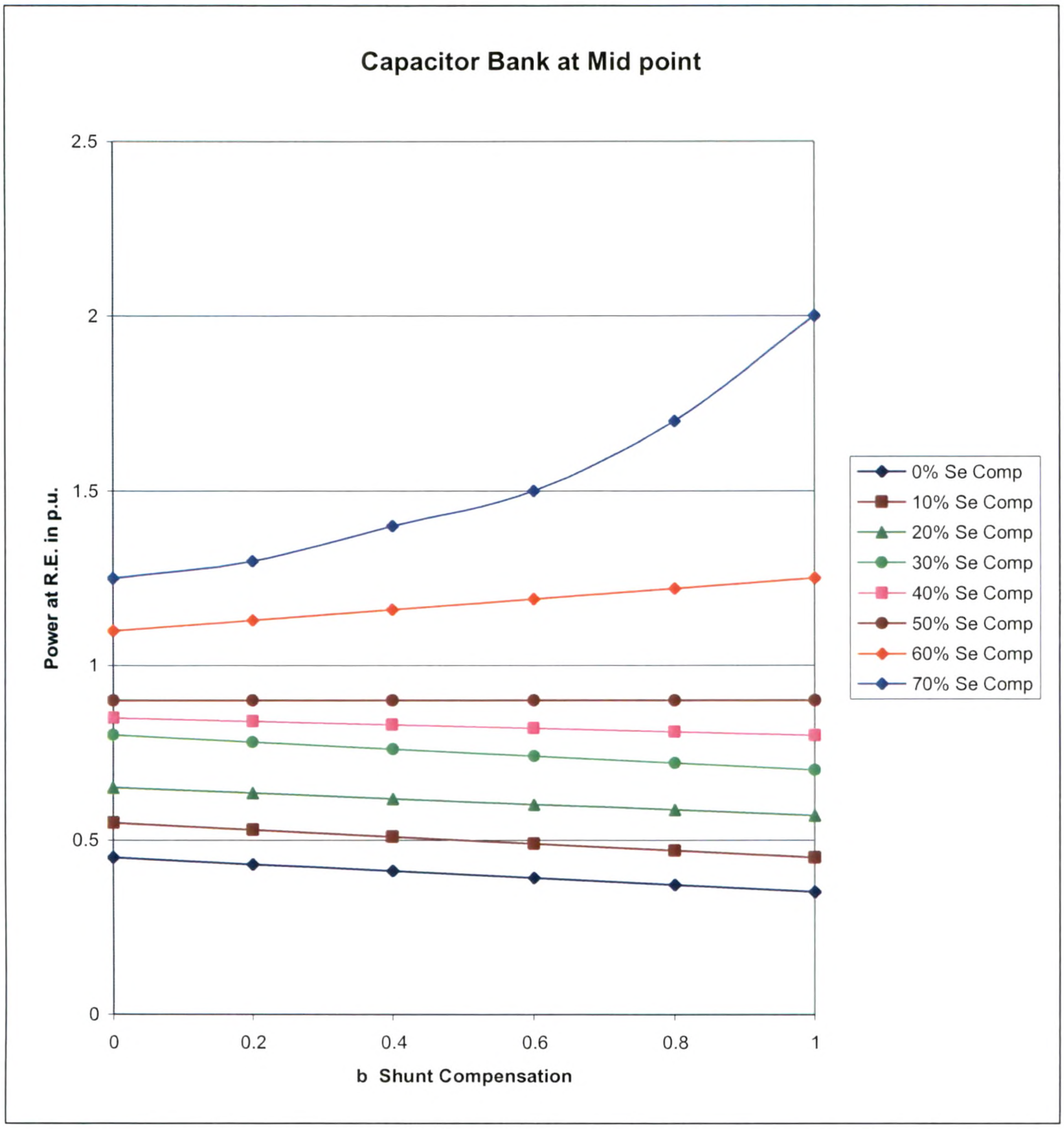


Fig. 5.7 Effect of Series and Shunt Compensation on Transmission Line Capacity, keeping Capacitor Bank at Mid-point of the Line

Figure 5.8 shows the variation of Ferranti over-voltage in a 60 percent series compensated line for different capacitor locations and shunt compensations. The effect of shunt compensation in reducing the Ferranti over-voltage is predominant only when it is placed at the receiving end of the transmission line. For other locations, the series capacitor itself reduces the power frequency over-voltages considerably.

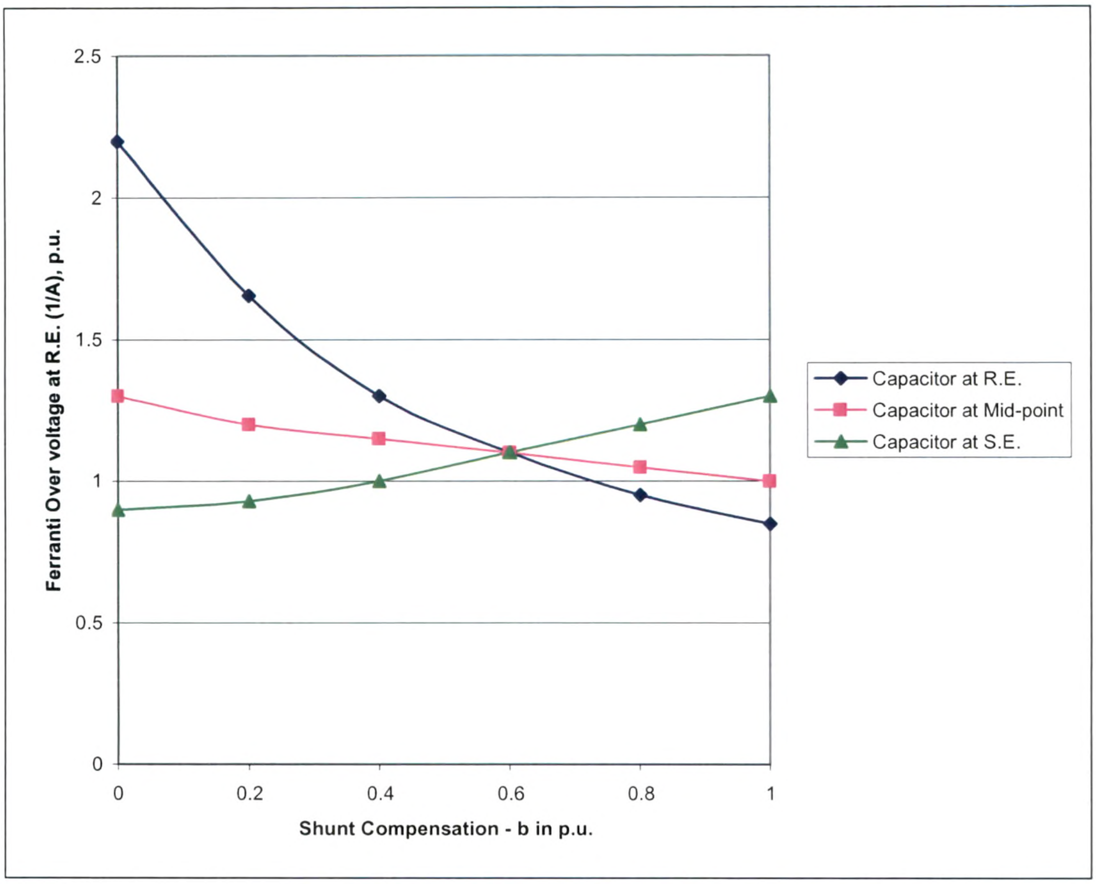


Fig. 5.8 Effect of Shunt Compensation on Ferranti over voltage

5.6 Conclusion:

Salient Points from Compensation Study:

1. The net transfer reactance is not just the arithmetic difference between the total inductive reactance and capacitive reactance of series capacitor but it depends on "Degree of Series Compensation", "location" of the compensation bank along the line, the line length and the number of series capacitor banks over which series compensation is distributed.
2. For the longer lines, the resultant transfer reactance will be more than the above value due to line charging effect. In order to account for this discrepancy, the term

"Compensation Efficiency" is introduced and this indicates effectiveness of the series capacitor in reducing the transfer impedance.

3. The Compensation Efficiency (K) is defined as the ratio of the net reduction of transfer reactance to the reactance of the series capacitor used.
4. Transfer impedance is minimum, when the Series Capacitor Bank is located at the center of the line.
5. The effect of line resistance shifts optimum location of the Capacitor Bank slightly towards the receiving end.
6. The effectiveness of the series compensation decreases with the increasing line length. However, this effectiveness increases with order of transmission for the same amount of increase in power transfer.
7. It is, however, found that at low degrees of Series Compensation, Compensating Efficiency with Two Capacitor Banks is slightly less than that obtained with a Single Capacitor Bank. This, in fact, is the reason for the requirement of higher MVAR rating for two capacitors at one-third points than for one capacitor at mid-point.
8. It is, however, noticed that beyond the critical shunt compensation value, the compensation efficiency increases, and thereby the power transfer capability also increases. The value of the critical shunt compensation (b_{cr}) is just the value of shunt compensation beyond which the transfer impedance of the line starts decreasing from the value corresponding to zero shunt compensation.
9. The term, "optimum shunt compensation (b_{opt})" It is at this point that the transfer impedance changes the direction of its variation
10. The compensation efficiency decreases considerably with the increase in shunt compensation, when the capacitor bank is located in the vicinity of the mid point of the line. However, at higher values of series compensation the effect of shunt compensation tends to increase the compensation efficiency for all positions of the series capacitor bank.
11. The effect of shunt compensation in reducing the Ferranti over-voltage is predominant only when it is placed at the receiving end of the transmission line. For other locations, the series capacitor itself reduces the power frequency over-voltages considerably.