CHAPTER IV

LOADABILITY CHARACTERISTICS OF MULTI PHASE LINES

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4.1 INTRODUCTION

Line loadability curves have been a valuable planning tool for the three-phase transmission systems since their first introduction by St. Clair [89] in 1953. A wide spread use of these curves has resulted in its extension to EHV and UHV levels [90]. Initially, thermal limit, voltage drop and steady state stability limitations to line loadability, were considered. An extensive simulation and analysis have revealed that thermal duty, line voltage drop and steady state stability limitations are the main controlling factors for line loadability of short, medium and long lines respectively [90, 91] for voltage up to 345 KV. As the system voltage increases, the terminal system reactances (electrical strength of the system) also become a vital factor in determining loadability characteristics [90].

A significant development in this area makes it possible to incorporate specific operating conditions under which a line has to work, identify and determine the overall limitations to power transmission across a line. The power carried by the line is plotted as curves by employing thermal duty, bus voltage and steady state stability, as the limiting criteria. These curves are appropriately known as operating loadability characteristics of the line [91] which yield realistic power loadability as well as main limitations to the line loadability. Yet, further developments [92] examine critical dependence of line loadability on Var supplies and incorporate effects of load voltage characteristics, transformer taps, distributed nature of line parameters etc. for determining reactive power constrained loadability limits [93].

Multi-phase transmission systems, especially the six-phase and twelve-phase, are being developed as potential alternative to the conventional three-phase systems. Among the interesting features of multi-phase transmission, the increased power transfer capability and efficient utilization of right of way are known to be the most attractive ones. However, before the multi-phase systems are actually planned, an assessment of the benefits of these lines, in terms of their loadability as constrained by several system performances and operating environment criteria, must be made with regard to their lower phase order counterparts. A literature survey reveals that no systematic study of multi-phase line loadability characteristics has been carried out so far. This chapter is, therefore, devoted to the construction and investigation of loadability characteristics of multi-phase lines by applying some of the concepts and constraints reported for the three-phase systems [90-93].

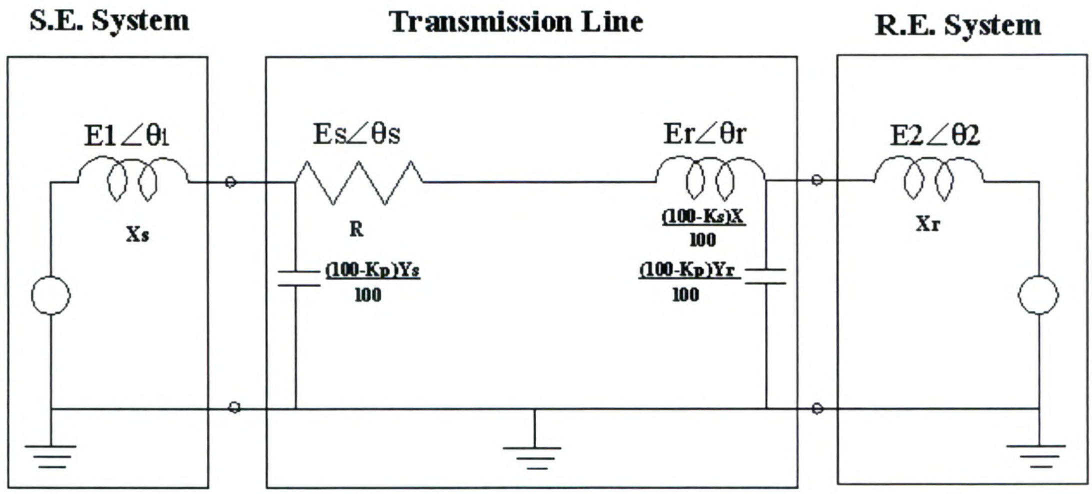
The basic analytical model of the line for obtaining loadability characteristics considering voltage drop and steady state stability margin are delineated in section 4.2.1; and the procedure to derive generalized loadability curves is explained in section 4.2.2. The section 4.2.3 is concerned with the evaluation of operating loadability curves which depend upon the limitations under which the transmission line operates. The loadability dependence on Var supply is studied and line loadability limits consistent with Var supply limits are determined in section 4.2.4. Finally in section 4.3, specific EHV test systems are employed to construct loadability characteristics curves to bring out relative benefits of multi-phase lines as well as the circuit uprating applications. The important findings of the study are concluded in the section 4.4.

4.2 BASIC ANALYTICAL APPROACH AND THEORETICAL FRAMEWORK:-

The basic circuit model, analytical approach, and the necessary theoretical background used in the present study will be briefly discussed here.

4.2.1 Basic Circuit Model:

The basic circuit model for line loadability analysis is essentially that of References [90, 91] adapted for multiphase lines represented on single phase equivalent basis as shown in Fig. 4.1. This circuit model consists of three main parts, the transmission line and the two systems connected at the transmission line ends and represented as shown in fig. 4.1 below.



(Ks / Kp : Degree of series and shunt compensation)

Fig. 4.1 A Circuit model for line loadability study

(i) Each system is represented by the positive sequence Thevenin's equivalent. The terminal system impedances (x_s and x_r) are obtained from short – circuit analysis. E_1 and E_2 are specified as voltage magnitudes of the sending end and the receiving end systems, respectively.

(ii) The transmission line is represented by the equivalent π– circuit using positive sequence parameters, where K_S and K_P indicate the degree of series and shunt compensation respectively.

4.2.2 Derivation of Generalized Loadability Curves:-

For the purpose of this investigation, the loadability is defined as the power computed at the sending end expressed in per unit of surge impedance loading (SIL). When the loadability with constraints on thermal duty, voltage drop, and steady state stability margin limits are plotted as function of line length, the curves are referred as generalized loadability curves. Since the thermal capability is significant just for very short lines at voltage levels of 138 KV and below, only the practical limitations on line loadability as provided by voltage drop and steady state stability margin are taken into account for further discussion hereafter. The following procedure is adopted to generate the required data for obtaining the curves.

(i) The voltage magnitudes of the sending end and the receiving end systems i.e. E_1 and E_2 are specified (based on A.C. base case load flow). However, these values are taken as 1 and 0.97 per unit in the present case. The voltage drop limit (say 5%) and stability margin (say 30%) are specified.

(ii) Taking an initial length of the line to be 50 Kms., and angle of E_1, the voltage E_r is derived and computed as follows :

$$|E_r| = |(2ZE_2 + jC_3E_1) / (C_1 + C_2)| \tag{4.1}$$

Where,

$C_1 = 2Z + jX_2 (2 + ZY)$: $C_2 = 4X_1 X_2 / C$

$C_3 = 4X_2Z / C$: $C = 2Z + jX_1 (2 + ZY)$

Y = total shunt admittance of transmission line and $|E_r|$ is then tested for the required voltage drop criterion. If the maximum voltage drop limit is just met, the loadability is said to be voltage drop limited, and E_s is computed as:

$$E_s = (2ZE_1 + j2X_1E_r) / C \tag{4.2}$$

This is substituted in (4.3) to calculate the sending end power (Ps) as follows:

$$P_s = - \{[\ |E_s|\ |E_r|\ ]/\ |B|\} \cos(\beta + \delta) + \{[\ |A|\ |E_s|^2 /\ |B|\} \cos(\beta - \alpha) \tag{4.3}$$

Where, A and B are the generalized parameters of the transmission network including compensation devices; and δ is the angle between the voltages E_s and E_r. The P_s divided by SIL yields the loadability in per unit.

(iii) If the voltage drop limit is not encountered, angle θ is incremented, and E_r is computed vide (4.1) as in step, (ii). If the limit on θ is reached in the process, the loadability is said to be steady state stability margin limited as illustrated in the central solution loop shown in Fig. 4.2. In this case, E_s and P_s are calculated vide (4.2) and (4.3); and loadability is computed in per unit of SIL.

(iv) Next, the length of line is incremented and the aforesaid sequence of computation is carried out till the required line length.

4.2.3 Derivation of Operating Loadability Curves:-

The line operating loadability is defined as the loading limits of the transmission line determined under the constraints influenced and modified by system environment under which the line is operating. The operating loadability curves are constructed utilizing the basic model (Fig. 4.1) by following the procedure outlined as under.

(i) The voltage magnitudes of the sending and the receiving end systems are determined as explained in section (4.2.2).

(ii) The line parameters are computed for a complete length of line, and the terminal system impedances are calculated on the basis of electric strength (or fault duty) of the system.

(iii) An initial value of the angle θ_l is taken to start the computation. The voltages E_r and E_s are calculated using (4.1) and (4.2) respectively.

(iv) With the values of θ_l, E_r and E_s, the power flow at the sending end of the line is computed vide (4.3). For this power flow, thermal power (E_s times I_s) and angular separation for the complete system (θ_S) as well as for the line θ_L, are evaluated and recorded.

(v) The steps (iii) and (iv) are repeated by increasing the initial value of θ_l until it reaches its maximum value of 90 degrees.

The computed values of thermal power, bus voltages and angular displacements are plotted as functions of the power flow. These curves are known as the operating loadability curves.

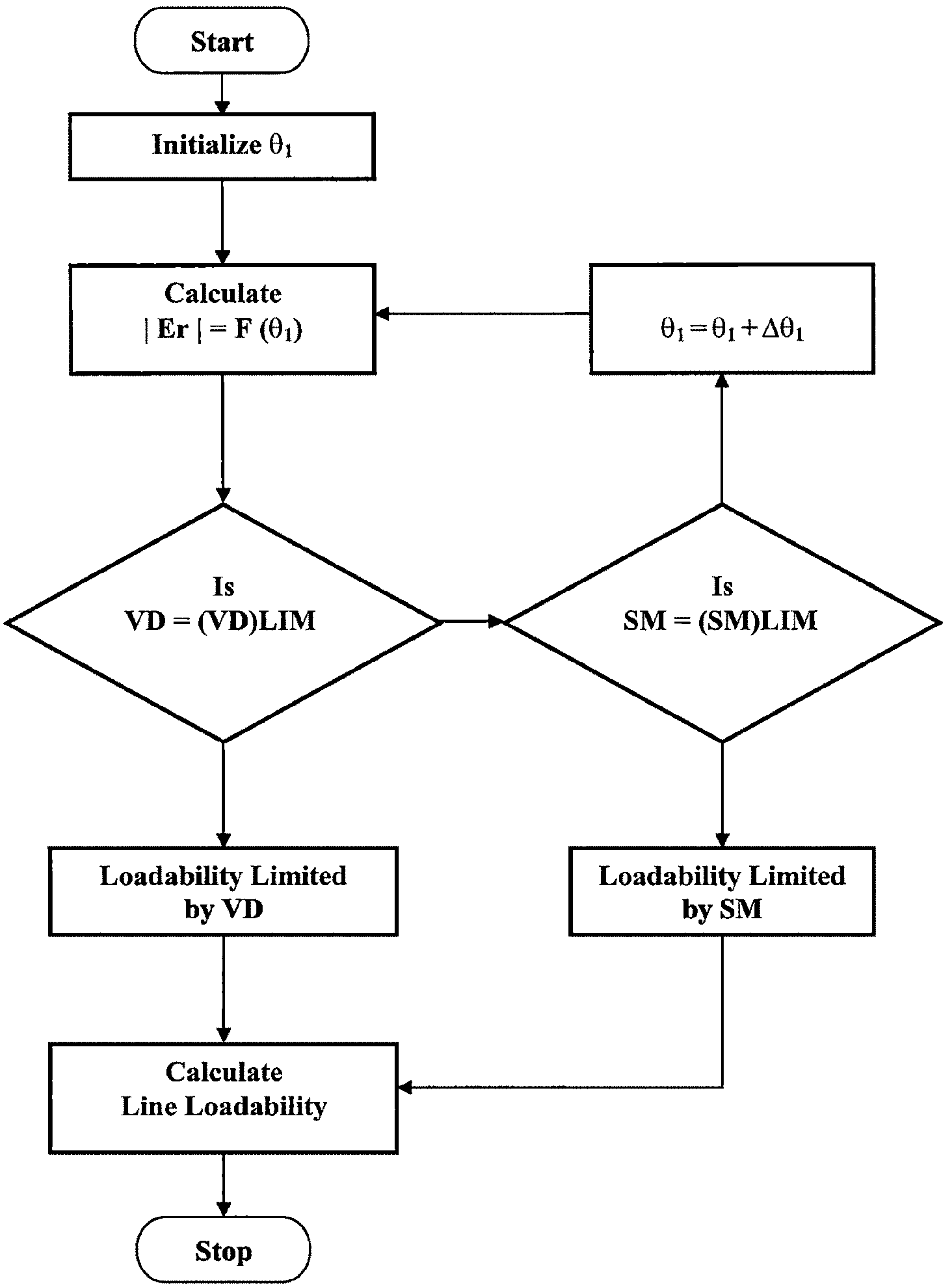


Fig. 4.2 Flowchart of central solution loop

4.2.4 Loadability Dependence on Var Supply:-

The St. Clair loadability curve and its analytical equivalents imply unlimited Var reserves to maintain voltages at the line terminals. Their applicability, therefore, hinges largely on Var reserve capability. With reference to Fig. 4.3 (With $K_S = 0$) it has been shown [92] that the Var limits must be sufficient enough to allow operation at an angle displacement between sending and receiving end voltages of -90°, even though the normal operation will be limited to an angle of -44° to ensure a 30° steady state stability margin. If the Var capabilities are specified to control voltage only to a displacement of say -44°, the true stability margin may be zero. The stability margin is applicable only to the transmission lines with unlimited var supplies. In situations where the Var supply is limited, the loadability limit is described by voltage stability rather than steady state stability. However, the maximum Var capability will largely determine the operating point voltage and operating point stability margin. Thus, the maximum Var capability is also critical in the evaluation of maximum power transfer and critical angular separation.

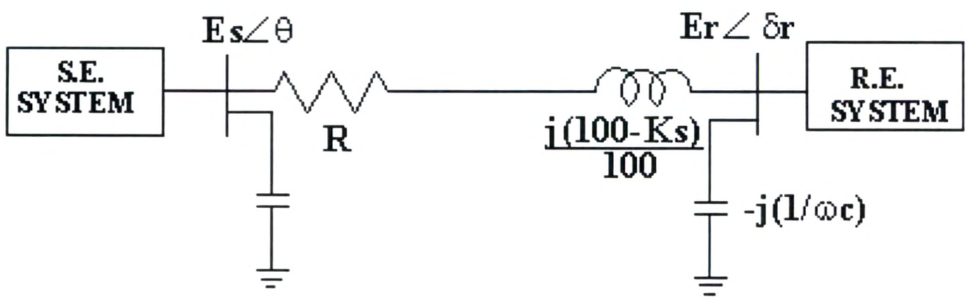


Fig:4.3 A Line Model for Loadability Dependence on Var Supply

With the above objective in view, the maximum value of Var reserve (Q_m) at the receiving end bus (ensuring an acceptable operating point voltage E°_r ($\geq E_r$) and operating point stability margin s.m.° ($\geq$ s.m. $_{des}$)) is determined by employing Kay's ten step algorithm

[92] as given in Appendix A, with and without series compensation for multi-phase transmission lines, for the pre-specified values of :

(i) Operating point load P°_{r}.

(ii) Minimum acceptable voltages $\underline{E}_{r}$.

(iii) Desired value of stability margin (s.m. $_{des}$).

(iv) No lower bound on injected Q.

4.3 TEST SYSTEMS AND EVALUATION OF GENERALISED LOADABILITY CURVES :-

In order to construct and evaluate loadability characteristics curves, for transmission alternatives 3-phase double circuit system and 6-phase system with the same number of conductors, same right-of-way and utilizing the same air space for transmission (see Chapter II, Fig. 2.3) are considered. Each system is energized at 400 KV line-to-ground voltages and has the same thermal rating. The line parameters based on the assumptions of complete transposition of conductors are given below:

* 2x3-phase line : $z = 0.02758 + j0.1575\ \Omega$ / Km

$y = j7.61814\ \mu S$ / Km

* 6-phase line : $z = 0.02758 + j0.3985\ \Omega$ / Km

$y = j\ 2.82986\ \mu S$ /Km

4.3.1 Generalized Loadability Curves:-

Employing the data given above, and following the procedure outlined in section 4.2.2, the ratios of the sending end power to SIL have been computed and plotted against line lengths between 50 and 1000 Kms. for both the alternative transmission systems. Fig. 4.4 shows the generalized loadability curves for a 400 KV (L-G) three-phase double circuit lines and six-phase lines respectively.

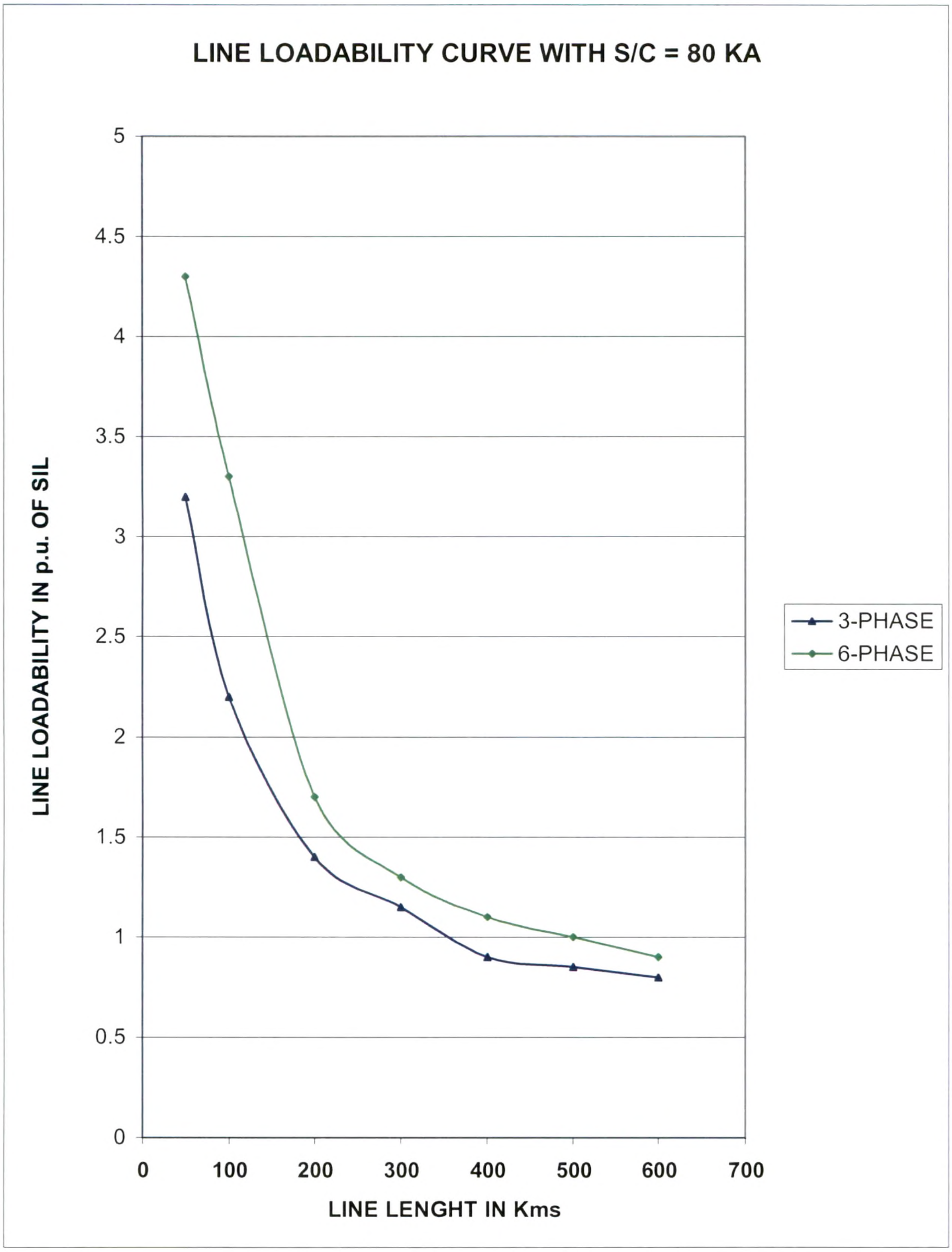


Fig. 4.4 Generalized loadability curves for 400 KV alternative lines.

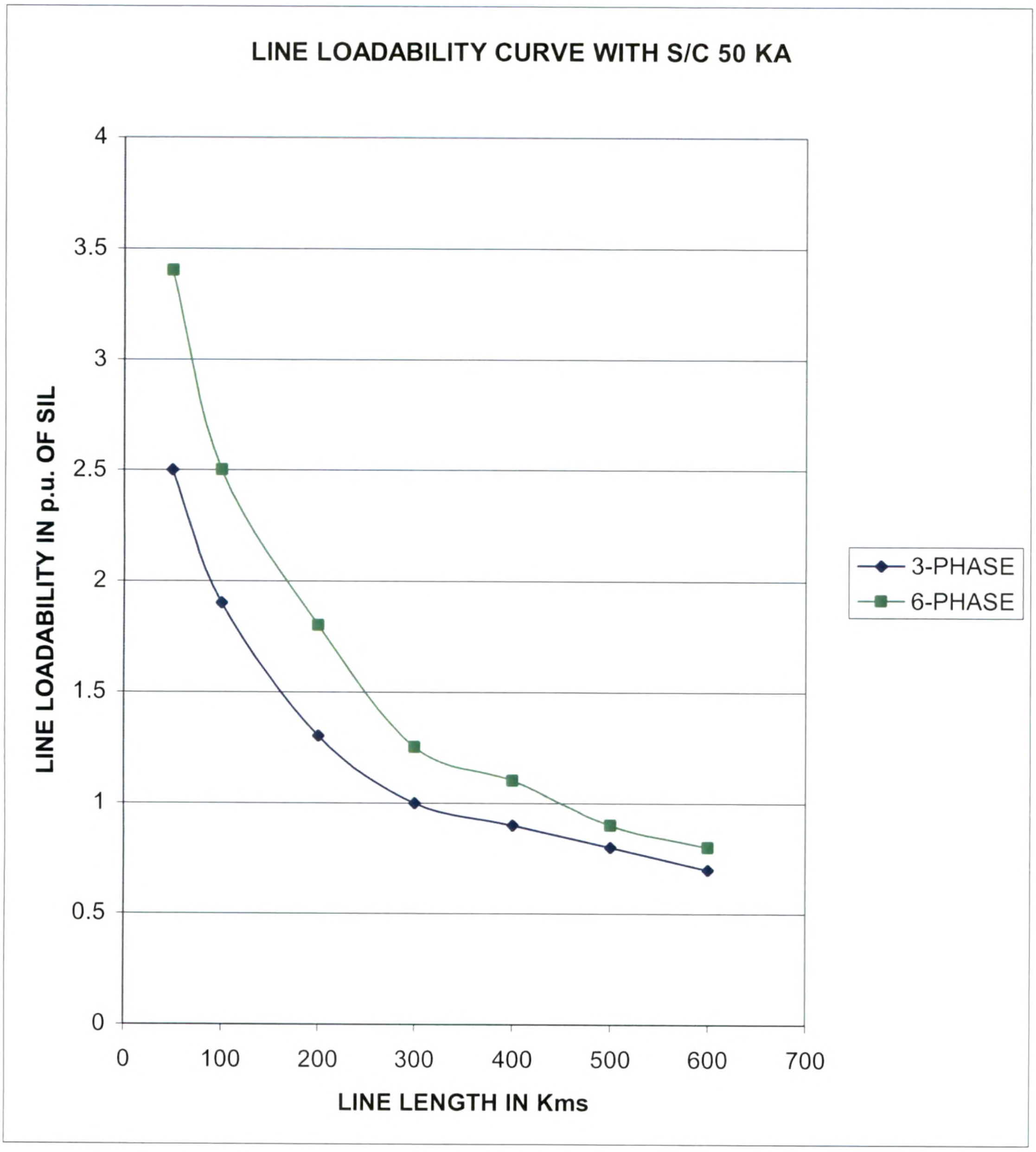


Fig. 4.5 Loadability curves for 400 KV alternative lines.

Effect of terminal system impedance:-

The effect of terminal system impedances on line loadability of multi-phase systems under the same performance criteria (i.e. 5% voltage drop and 30% stability margin) is studied by varying the terminal system strength between 50 KA and 80 KA fault duty. It is observed that the loadability curves for six-phase lines show a marked effect as compared to that of three-phase lines for short lengths. This indicates that any increase in the terminal system strength leads to an enhanced line loadability of multi-phase lines.

Effect of shunt compensation:-

The effect of shunt compensation on line loadability is very little. The two transmission schemes show a negligible change in their loadability for a full range of shunt compensation between 0% and 80% at low terminal system impedances. In the case of high terminal impedances, the effect of shunt compensation is somewhat marked (although only slight), as evident from Fig. 4.6 shown below.

Effect of series compensation:-

Fig. 4.7 and Fig. 4.8 illustrate the variation of line loadability of the two transmission systems for changes in series compensation between 0% and 80% under the performance criteria of 5% voltage drop, 30% stability margin, and with terminal system strength of 50 kA fault duty. The effect of series compensation is considerably high and it goes higher with the increasing phase order. Besides, every additional percent of series compensation yields increasingly greater improvement in line loadability. It is also observed that line loadability for short length is of higher value and may exceed the thermal limit of the conductor. However, this study is just to indicate the effect of series compensation on multi-phase lines without going deeper into the technical and economic aspect of the problem.

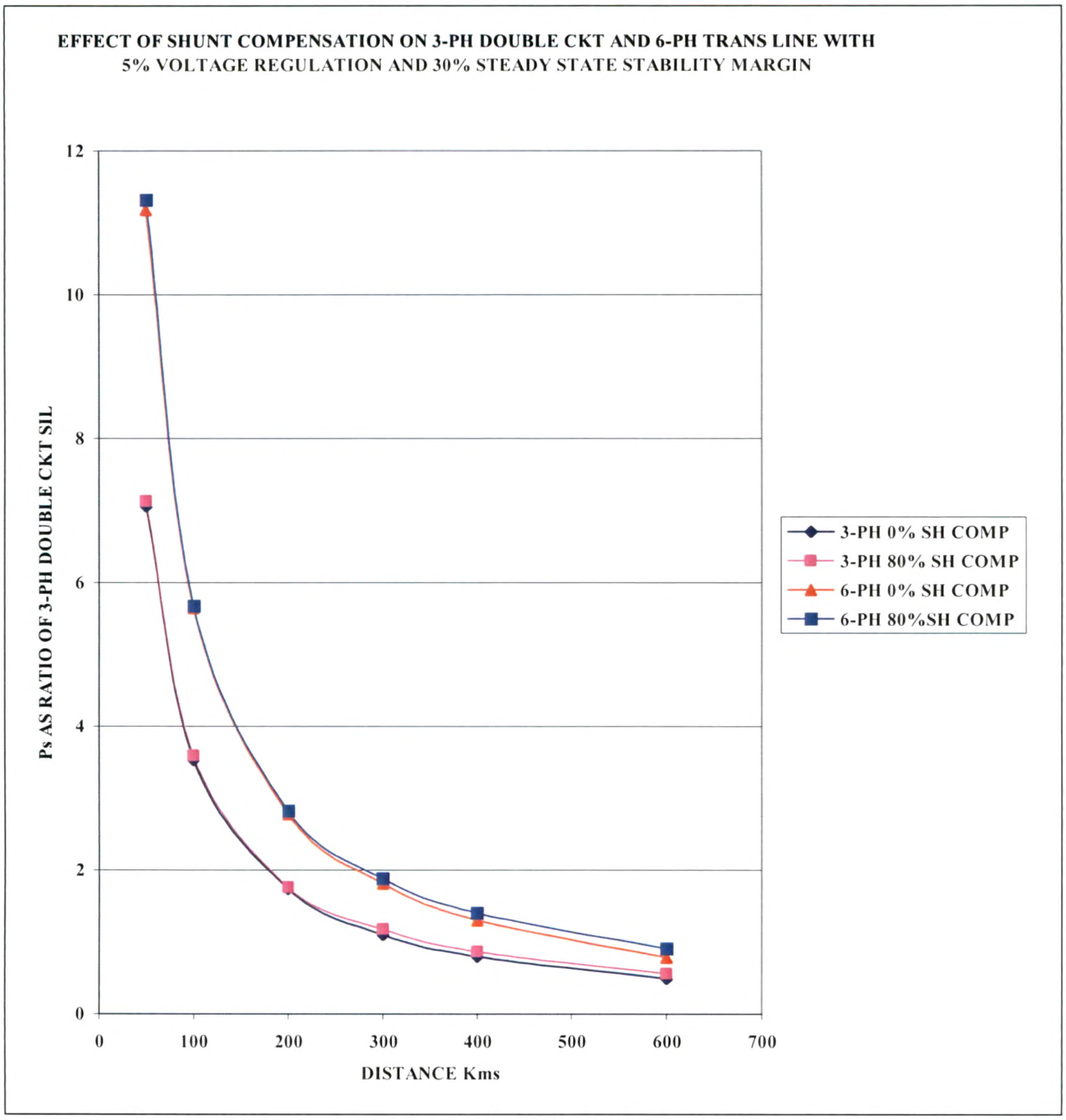


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Fig. 4.6 Effect of Shunt Compensation on Line Loadability

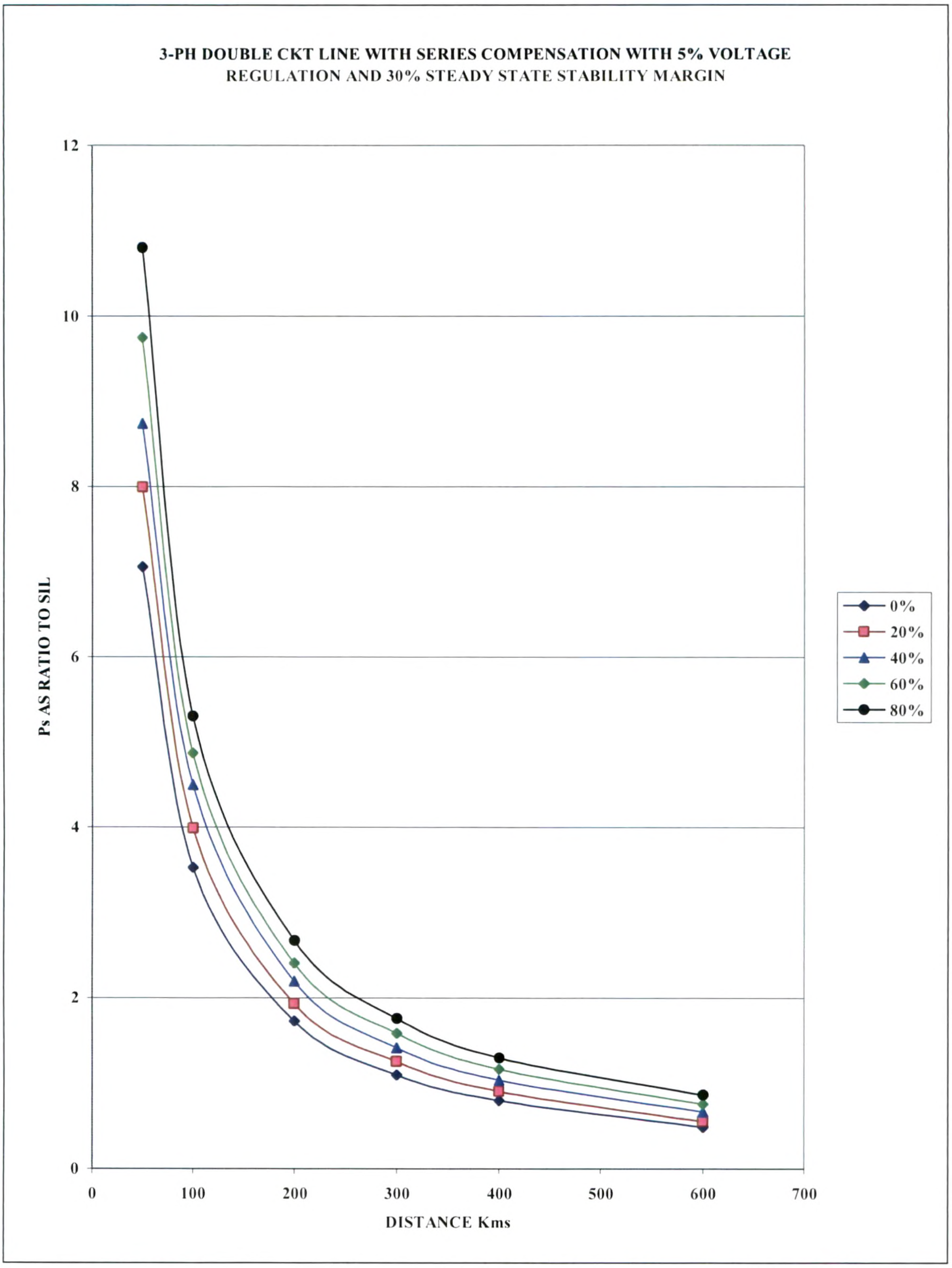

Fig. 4.7 Effect of Series Compensation on GETCO'S three-phase Double Circuit Line Loadability

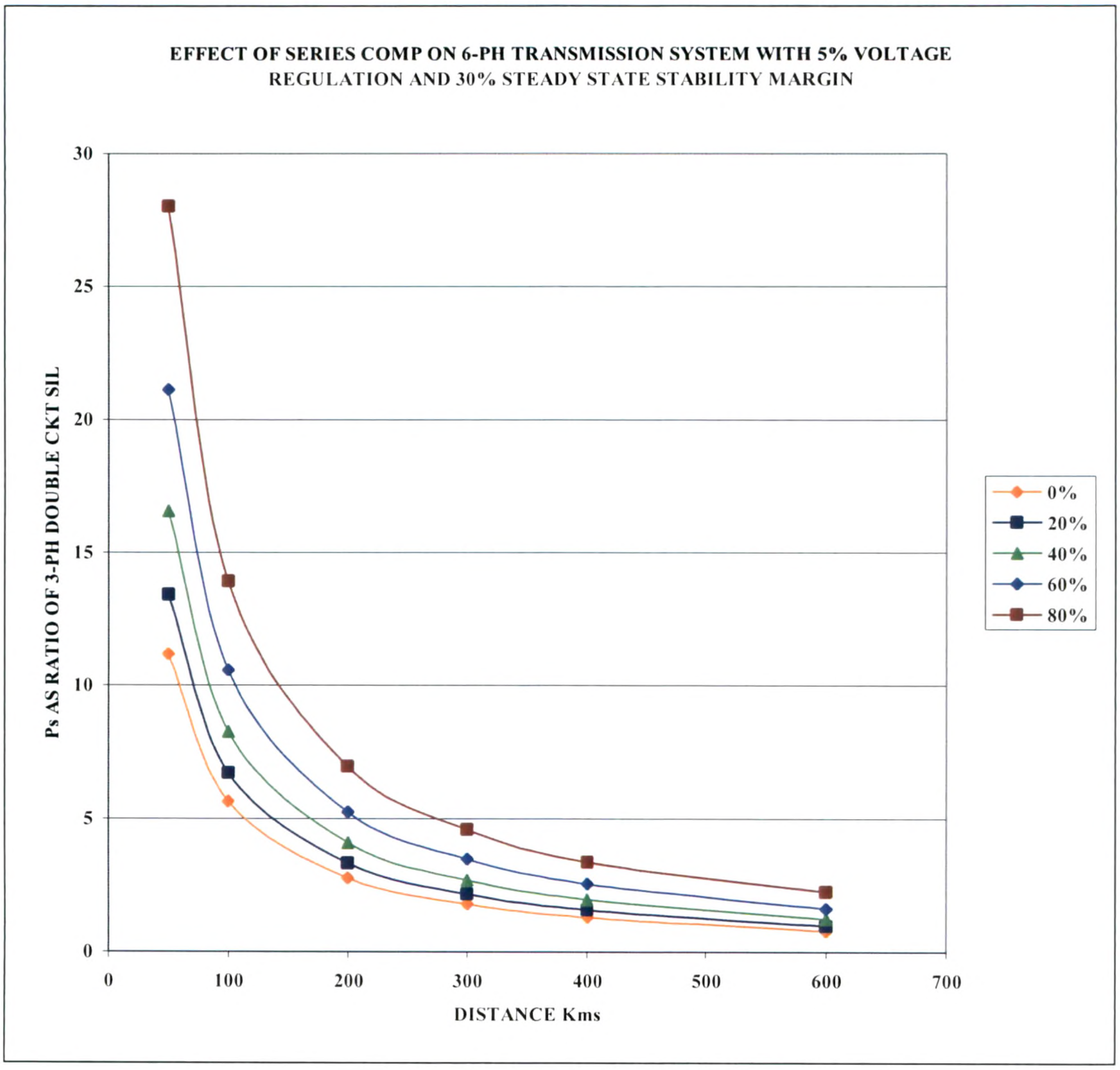

Fig. 4.8 Effect of Series Compensation on (GETCO'S three-phase Double Circuit Line Converted in to Six-phase) Six-phase Line Loadability

Effect of voltage drop criterion:-

Fig. 4.9 shows three sets of curves for the two transmission alternatives. Each set consists of three curves drawn for 6%, 5% and 4% voltage drop criterion. It is already known to us that any change in the line voltage drop affects the loadability of only the short and medium length lines. An increase in voltage drop improves the line loadability rapidly at first, and then gradually to a point where line loadability can only be improved by allowing a smaller steady state stability margin. Generally, the effect of any change in voltage drop criterion on line loadability is more pronounced particularly in the Six-phase lines as compared to that of the lower phase order lines.

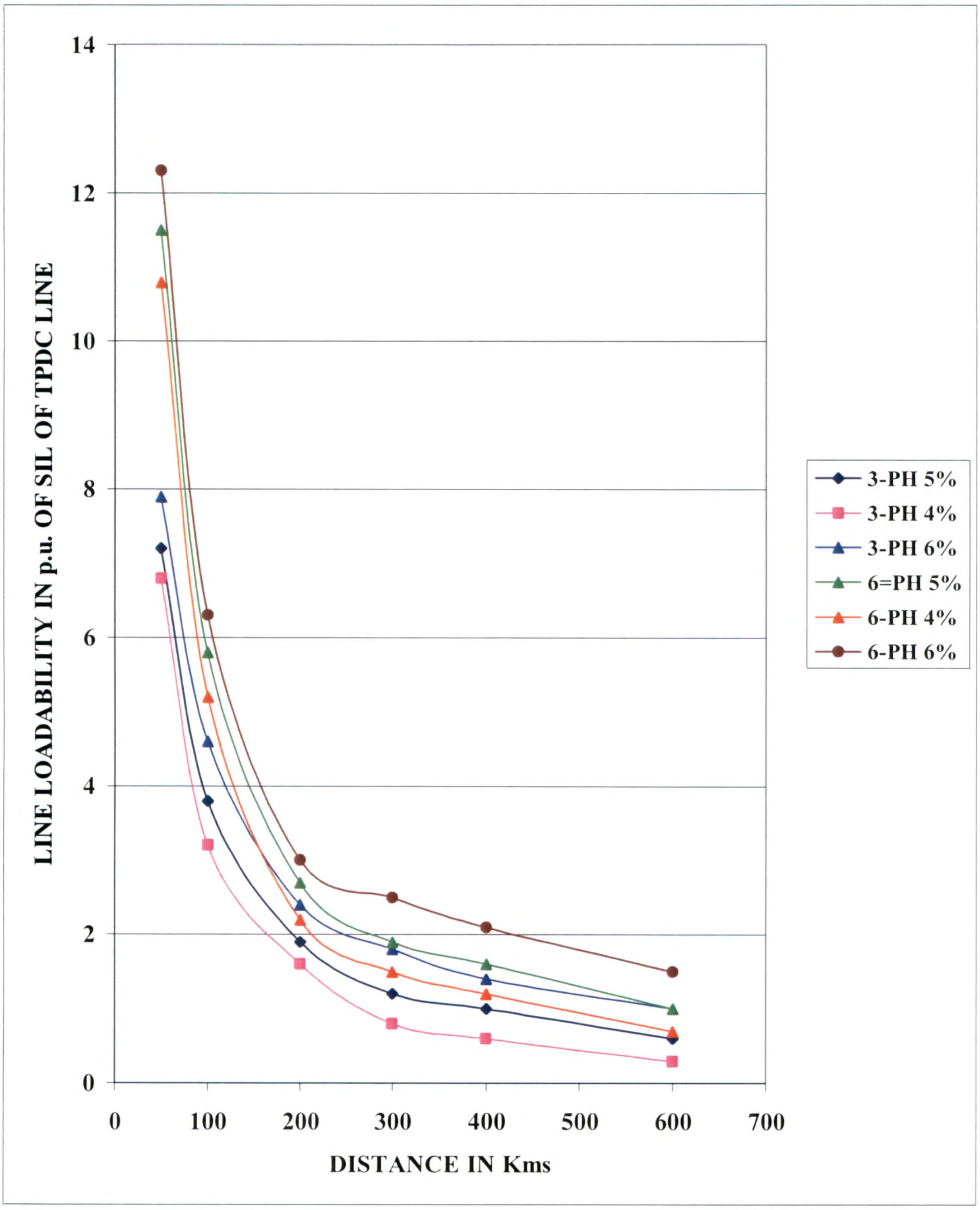

Fig. 4.9 Effect of Voltage drop Limit on Line Loadability

Effect of steady state stability margin:

The effect of varying stability margin on line loadability is depicted in Fig. 4.10. These curves show that an equal percent of reduction in stability margin yields almost equal sized increments in loadability of long lines, whereas short lines are not affected. The Six-phase line loadability curves have somewhat marked greater equal sized increments as compared to those of their lower phase order counterparts. In brief, the smaller the stability margin the higher is the line loadability of multi-phase lines.

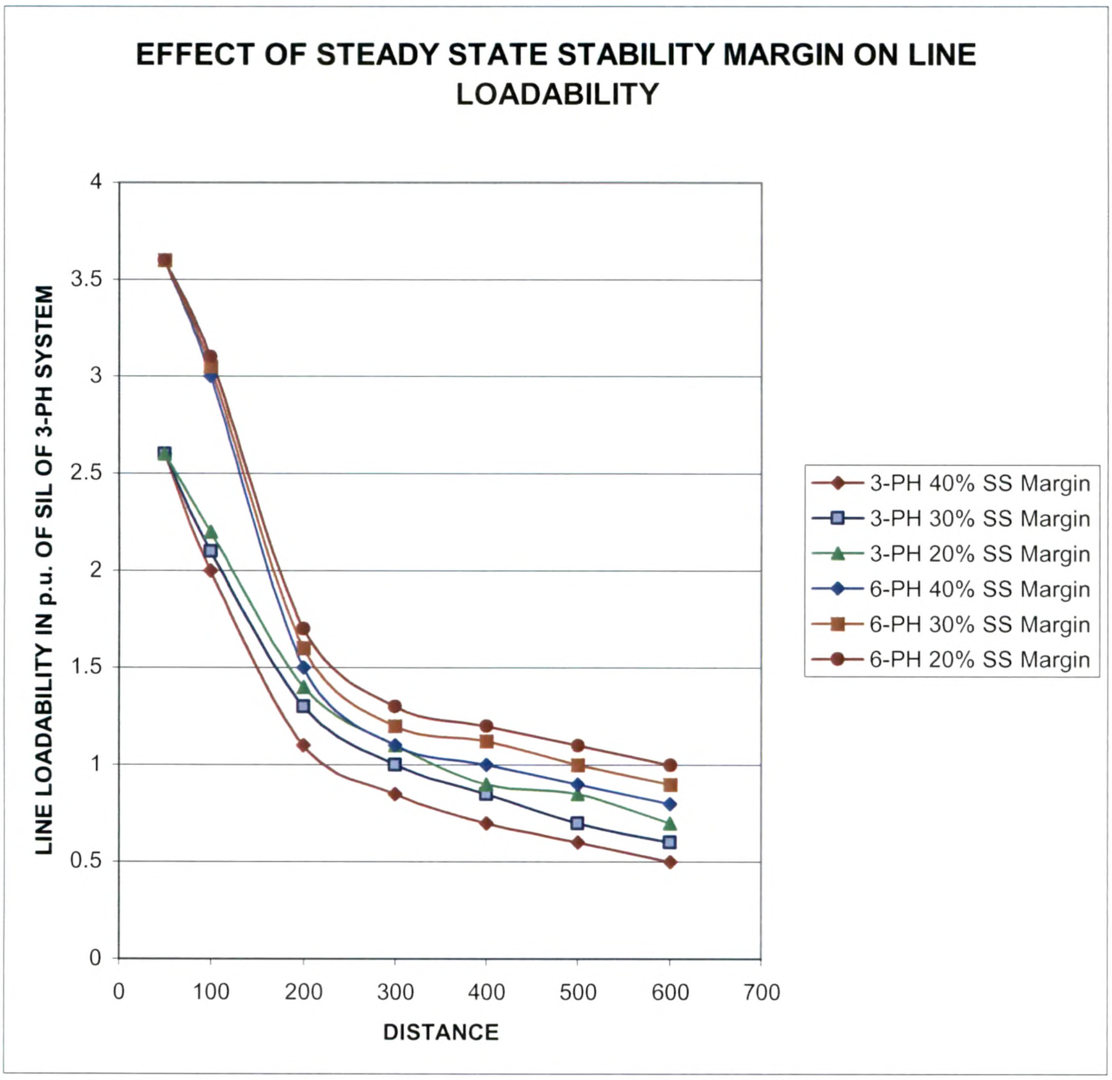

Fig. 4.10 Effect of Variation of Steady State Stability Margin, on Line Loadability for 3-phase and 6-phase Transmission Systems.

Quantitative benefits with multi-phase option including circuit uprating applications:-

In order to quantify the additional power transfer with multi-phase lines, the loadability curves for the three alternative transmission systems under the performance criteria (5% voltage drop and 30% stability margin) and same the terminal system impedances are redrawn in Fig. 4.11 with the sending end power in each case expressed as per unit of SIL of three-phase and six-phase lines. It can be observed that additional power transfer capability to the tune of 71% to 83% in six-phase over three-phase is available along the line span considered. It may be noted that these benefits are obtained with the same line structure and the same phase to ground voltage in each case. However, the ultimate loadability benefits will be modified and dictated by the operating criteria in practice.

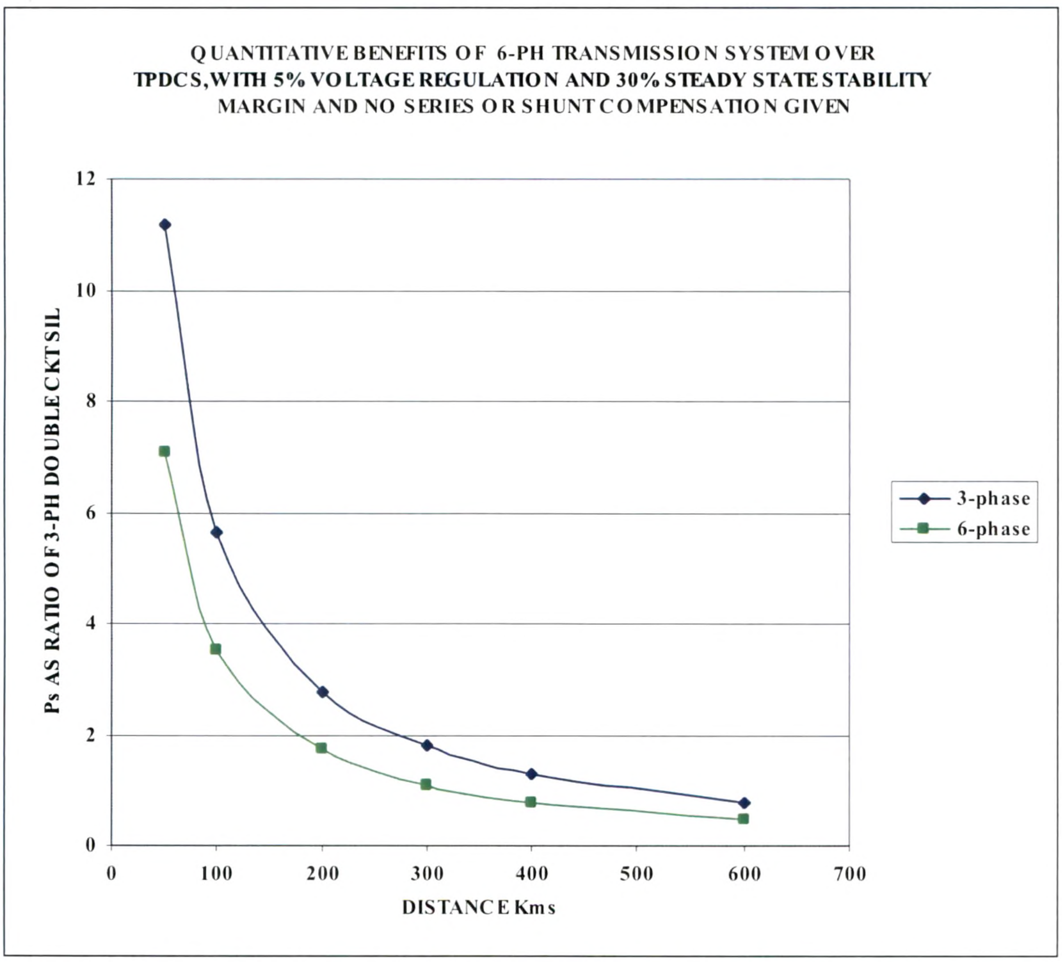

Fig. 4.11 Quantitative benefits in line loadability with multi-phase system

In order to evaluate the benefits of a six-phase conversion of a conservatively built double circuit three-phase line solely in terms of line loadability, a 400 kV 2x3-phase network (see chapter II, Fig. 2.3) is considered with the following circuit parameters:

* 2x3-phase line : $z = 0.02758 + j0.1575\ \Omega$ / Km
  $y = j7.61814\ \mu S$ / Km
* 6-phase line : $z = 0.02758 + j0.3985\ \Omega$ / Km
  $y = j\ 2.82986\ \mu S$ /Km

As a result of uprating of the existing 2x3-phase line to six-phase line, the adjacent line to line voltages remain the same in both the cases and also the same conductor currents and power factors are assumed in both the modes of operation. The loadability curves of both the alternatives are shown in Fig. 4.11. It is seen that an additional power transfer capability of around 75% (only 73% without constraining E_r for a 5% drop; and neglecting terminal system impedances) is available throughout the span of the line considered. It is further verified that the same additional benefit is obtained, if the 2x3-phase circuit is up rated to √3 x 400 KV [32]. Thus the six-phase operation is equivalent to a 2x3-phase double circuit line up-rated to √3 x 400 KV, as far as the line loadability is concerned.

4.3.2 Operating Loadability curves:-

Operating loadability curves as distinguished from the generalized loadability curves reflect the specific system conditions under which a transmission line operates. The important consideration in constructing the operating loadability characteristics is to arrest the effect of system contingencies resulting in reduced terminal voltages, reduced stability margin etc. By using the circuit model given in Fig. 4.1, and the parameters of the two alternatives given in section 4.3.1, the curves for thermal duty, bus voltage and angular displacement as a function of power flow across a given line (of length 200 Kms), are constructed (Fig. 4.12 to 4.14) as per the procedure outlined in section 4.2.3.

Fig. 4.12 describes the change in thermal duty as a function of the real power flow on three-phase double circuit and six-phase lines, respectively. The two curves are similar in nature where the thermal duty curve is linear over major portion of its length except for the heavy loading region. However, the six-phase line curve is accompanied with lower slope as compared to that of its three-phase counterpart.

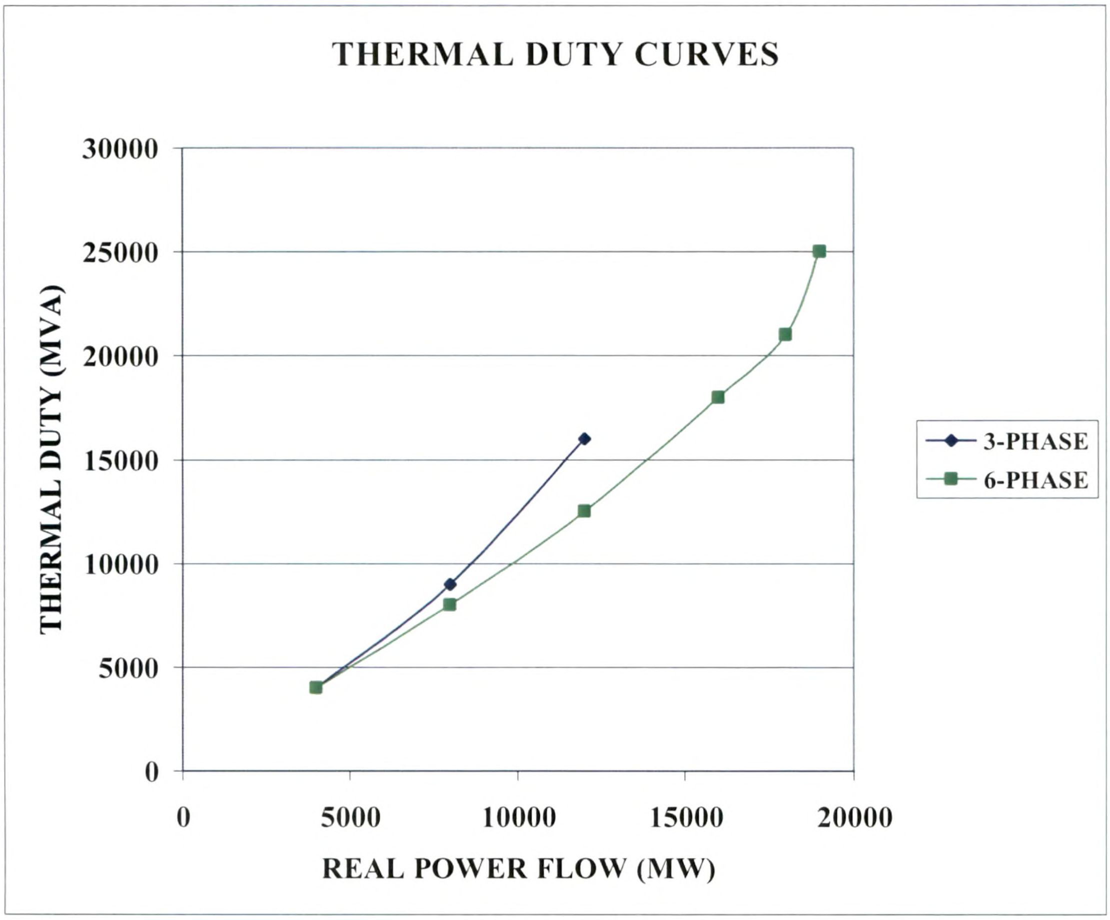

Fig. 4.12 Thermal Duty Curves

Fig. 4.13 shows the dependence of bus voltages E_s and E_r on power flow for the two transmission alternatives considered. An examination of these curves reveals that with the increases in power flow there is a rapid deterioration in bus voltages for three-phase system; while in the case of six-phase system rate of deterioration in bus voltages is progressively slower. If a 10% decline in voltage can be tolerated, a power transfer possible with three-phase line is only of 9643 MW; while with the six-phase line it will be 17637 MW. A multi-phase line has better voltage performance especially during the heavy loading region with increase in phase order.

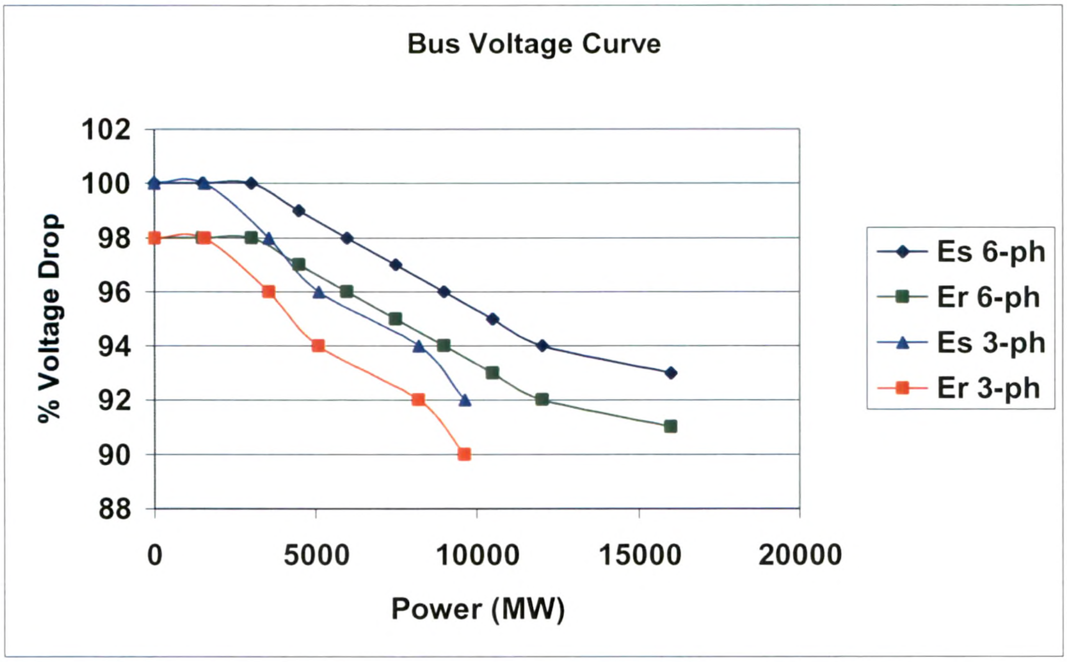

Fig. 4.13 Bus Voltage Curves for GETCO's 400KV three-phase Double Circuit Line and Its Conversion to Six-phase

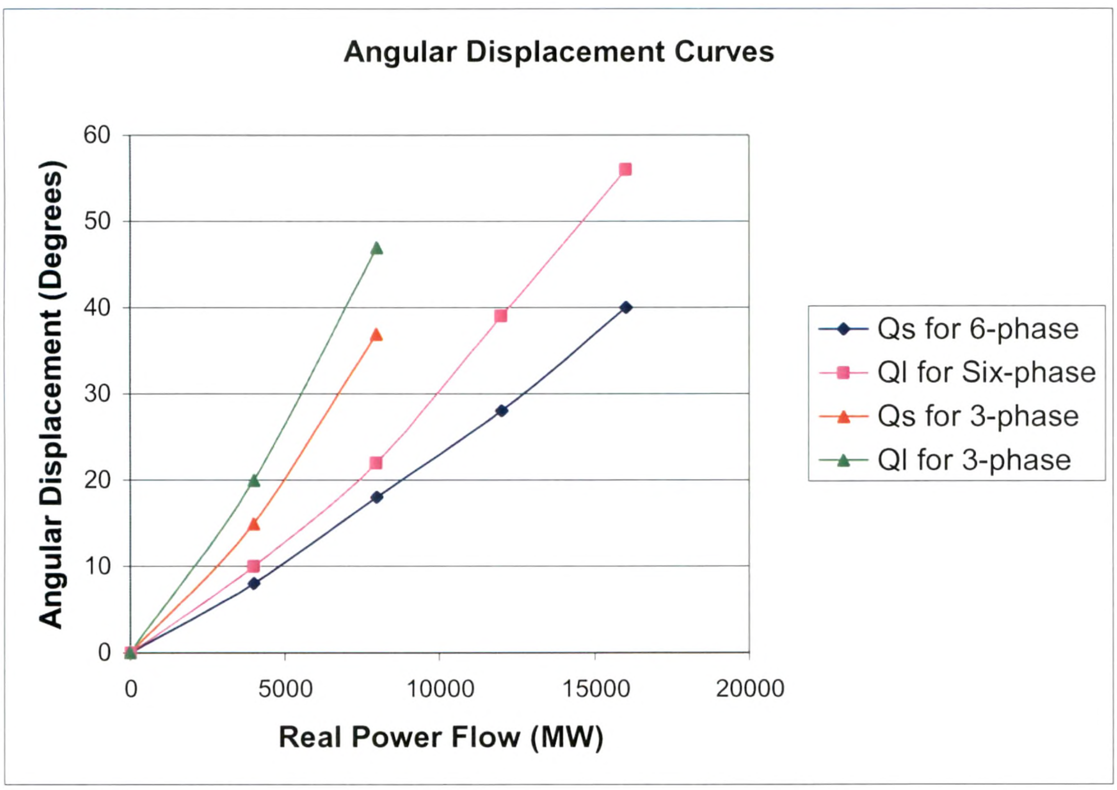

Fig. 4.14 Angular Displacement Curves GETCO's 400KV three-phase Double Circuit Line and Its Conversion to Six-phase

Fig. 4.14 shows the angular displacements θ_S and θ_L as a function of the line flows. The angular separation curves show progressively a lower rate of rise with power flow. This implies that of the two alternative schemes considered, the multi-phase lines maintain a significantly better stability margin during the heavy loading region.

Each of the curves (Fig. 4.12-14) demonstrates a possible limitation to the line loadability of the two alternative schemes. After specifying a given set of operating performance criteria, single valued loadability ratings for the two lines can be determined. It is evident that such ratings would be higher as the phase order increases. The multi-phase system, yields significant advantages during emergency, as compared to the conventional three-phase system.

4.4 CONCLUSIONS

In this chapter, the existing three-phase concepts and techniques have been extended and employed to construct loadability characteristic curves for EHV six-phase transmission lines. The procedures to obtain the general and operating loadability curves and loadability dependence on Var supply capability are discussed employing the specific multi-phase line. Based on the results obtained in the present study, with particular reference to the two alternative transmission systems (employing same phase-ground voltage, the same number of conductors, same right-of-way and the same air space for transmission) the following conclusions my be drawn:

- Multi-phase transmission lines offer more power transfer for the same performance criteria (voltage drop and stability margin) as compared to that of three-phase system. The benefit in terms of line loadability increases with an increasing phase order.
- An increase in the system strength, series compensation and voltage drop, leads to an increased line loadability as the phase order increases, whereas a decrease in stability margin results into an increased line loadability with phase order increase.
- The shunt compensation has almost a very negligible effect.

- A six-phase up-rating of a 2x3-phase line yields around 75% benefit in line loadability under the same specific performance criteria for three-phase and six-phase modes of operation. However, when the terminal system impedances are neglected and 5% voltage drop constraint on receiving end voltage is dropped, only 73% benefit in line loadability is achieved.
- Multi-phase lines give better voltage performance and maintain better stability margin, especially during heavy loading region.
- For an equal amount of power transfer, Multi-phase lines have good voltage regulation as compared to that of the three-phase double circuit system.
- Series compensation has got a marked effect on line loadability in both the systems as compared to that of shunt compensation.
- The amount of compensation required for the same increase in loadability margin is less with the Multi-phase lines as compared to that of three-phase double circuit system (i.e Var required for Six-phase system will be less than that of three-phase double circuit system).
- The requirement of minimum Var reserve for multi-phase lines is progressively lower as compared to that of three-phase lines at all levels of loadings. The effect of series compensation is to enhance these benefits proportionately.
- The conversion of three-phase double circuit system to six-phase is as good as up-rating the transmission line by $\sqrt{3}$ times its rated voltage.
- In view the facts stated above, it can be deduced that six-phase power transmission has less line loss, and as such it is more efficient than three-phase double circuit system.