POWER TRANSMISSION LINES LOADABILITY

by

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A thesis submitted to the Faculty of Graduate Studies of
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Dedicated to my son Raman

and

wife Penny

ABSTRACT

This thesis contains a generalized analytical basis for transmission line loadability curves. It presents an extension of the original loadability (St. Clair) curve into the EHV and UHV transmission levels. The approach coordinates surge impedance loading with voltage levels, power angle, thermal ratings, active power, reactive power and system-stability factors. Criteria for surge-impedance loading is extended to higher voltage levels. Useful expressions and loadability curves are derived for overhead lines with and without series-capacitor and shunt-reactor compensations. The effect of voltage increase at the sending end and variation in power angle (steady-state-stability margin) on the transmission line loadability is documented in the form of graphs. The use of bundled conductors at higher voltage levels is discussed. The effects of number of conductors in a bundle, intra-bundle spacing, phase spacing and conductor size on the transmission line loadability are discussed and corresponding loadability curves are derived.

It is shown that, for reasonable assumptions, the expressions derived are applicable to transmission lines of any voltage level. The loadability characteristics derived are nearly identical to the original loadability curve. The analytical approach to the transmission line loadability curves is simple. It enables the user to examine the specific situations and helps to make the preliminary design studies.

ACKNOWLEDGEMENTS

The author would like to express his deepest gratitude to his supervisor, Professor M.Z. Tarnawecky, for his esteemed guidance in the preparation of this thesis, as well as his encouragement and financial assistance throughout the period of course work. The author has benefited immensely from his association with Professor Tarnawecky for his contagious enthusiasm as a scholar and educator. The author will appreciate such a relationship for many years to come.

Appreciation is also expressed to I.S. Kaler, Professional Engineer, and other friends for their valuable guidance and assistance in every possible way.

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NOMENCLATURE

Most of the symbols are explained in the text when these are used for the first time. Subscripts have been used to identify the symbols with the appropriate quantities. For quick reference, a list of important symbols is given below. For the voltage, current and impedance a bar on the top of the letters represents magnitude of these quantities otherwise these are vectors.

A	- Bundle radius of a bundle conductor
C	- Capacitance of the line
GMR	- Geometric mean radius of bundle conductor
GMR_C	- Geometric mean radius of each sub-conductor
GMD	- Geometric mean of the distances between the phase conductor bundles
I	- Current at any point on the line
I_1, I_2	- Components of current
I_S, $\bar{I}_S$	- Sending end current
I_R, $\bar{I}_R$	- Receiving end current
L	- Inductance of the line
N	- Number of conductors in a bundle
N_{SE}, N_{SH}	- Amount of series and shunt compensation
P_S, P'_S	- Sending end active power component of uncompensated and series and shunt compensated line

P, P' - Surge impedance loading factors for active power component of uncompensated and series and shunt compensated line

Q_S, Q'_S - Sending end reactive power component of uncompensated and series and shunt compensated line

Q, Q' - Surge impedance loading factors for reactive power of uncompensated and series and shunt compensated line

S'_s - Sending end complex power of series and shunt compensated line

S, S' - Surge impedance loading factors for complex power of uncompensated and series and shunt compensated line.

S_B - Itra-bundle spacing

SIL - Surge impedance loading

V - Voltage at any point on the line

V_1, V_2 - Components of voltage

V_R, $\bar{V}_R$ - Receiving end voltage

V_S, $\bar{V}_S$ - Sending end voltage

X_a, X'_a - Inductive and capactive reactance at one foot spacing

X_d, X'_d - Inductive and capacitive reactance factors

X_L, X_C - Inductive and capacitive reactance

X'_C - Inductive reactance of the series capacitors

Z_C, Z'_C, Z''_C, Z'''_C - Characteristic impedance of uncompensated, series compensated only, shunt compensated only, series and shunt compensated line

Z_R - Receiving end impedance

$Z_{SO}, Z_{SS}, \bar{Z}_{SS}$ - Input impedance of the open circuited, and short-circuited line

Z_{SR}, $\bar{Z}_{SR}$ - Transfer impedance of the line

SMALL LETTERS

c - Capacitance per unit length

e - Exponential

f - Frequency

g - Conductance per unit length

j - Operator

k_1, k_2 - Constants

ℓ - Length of the line

n - Ratio of sending and receiving end voltages

r - Resistance per unit length

r_b - Actual radius of each conductor

r_B - Effective radius of bundled phase

y - Susceptance per unit length

z - Impedance per unit length

$\frac{dI}{dx}$, $\frac{dv}{dx}$ - Rate of change of current and voltage per unit length

α - Attenuation constant

β, β', β'', β''' - Phase constant of uncompensated, series compendated only, shunt compensated only, and series and shunt compensated line

γ - Propagation constant

θ_{SS} - Angle of sending end impedance

θ_{SR} - Angle of transfer impedance

δ_{SR} - Power angle - Phase angle difference between V_S and V_R

λ - Wave length

DEFINITION OF TERMS

The following terms are specifically defined for use throughout the thesis:

Power System	An electric transmission network comprising ac transmission lines, generators and loads.
Transmission Line	Any interconnecting tie between two power systems.
Stability	The ability of power system or interconnected power system to maintain synchronism.
Power Angle	Phase angle difference between ac voltage vectors at each end of an ac transmission line.
Steady-State-Stability	The ability of the power system to maintain synchronism when the power is increased very gradually.
Steady-State-Stability-Margin	The difference between maximum power transfer and rated power divided by the maximum power.
Surge Impedance Loading	The amount of power delivered over the line to the load at the receiving end when the load is equal to the characteristic impedance of the line.
Loadability	Power carrying capability of the transmission line under steady-state conditions.
Maximum Power	The amount of power delivered over the line when the power angle is equal to 90 degrees.

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CHAPTER ONE

INTRODUCTION

1.1 Transmission Line Capability

The subject of ac power transmission line capability has received periodic attention in the technical literature since 1941. The most comprehensive paper being that of Clarke and Crary[1]. The problem was analyzed mathematically and with the aid of network analyzer. Summarizing this work, St. Clair[2], published empirical curves in 1953 that expressed loadability of transmission lines in terms of Surge Impedance Loading (SIL) and line length in miles. These curves were based upon practical considerations and experience and were drawn without considering any kind of series or shunt compensation.

The effect of bundled conductors on SIL and transmission line capability was reported by Gabrielle[3], et al., in 1964. In his text published in 1966, R.A. Hore[4] provides a brief discussion and critical commentary on the subject.

The transmission line capability curves, have been a valuable tool for planning engineers ever since their publication in 1953. In 1967, the Planning Department of the American Electric Power Service Corporation, modified the original loadability curve. It made the curve applicable to lines of voltage classes higher than 345 KV and longer than 400 miles. This curve, like the original curve, was arrived at through practical considerations. This extended curve has

been widely accepted and used in various industry reports[5,6]. The EHV transmission line handbooks, published by EEI[7] in 1968 and EPRI in 1975 have both displayed St. Clair's curve as standard for the industry.

The wide spread use of these curves makes it necessary to develop and extend the application of these curves into higher voltage levels. This, unlike the development of existing curves, cannot be done by using "judgement based upon practical considerations and experience" for no such experience yet exists. The conception of the existing curves and their proven validity over many years clearly demonstrates their genuineness. It should be stressed that for higher voltage levels the loading limits depend upon a number of system parameters.

The expression "line capability" as traditionally used is easily confused with physical properties of a line such as thermal capability. A modified expression "line loadability" is used further onwards, in this thesis to describe the load carrying capability of a transmission line.

1.2 Intent of Investigation

This thesis is intended to provide the analytical approach to the determination of transmission line loadability curves. System parameters can have a significant impact on the line loadability in EHV/UHV range. The analytical

approach will enable the planning engineers to examine specific situations and to avoid misinterpretation of the generalized conceptual guides at higher voltage levels.

In this dissertion, an analytical basis has been developed for the St. Clair's line loadability curves. Basic principles of transmission line and power transfer theory are combined to produce idealized expressions in terms of Surge Impedance Loading, power angle and line length. These expressions are then used to derive a standardized analytical loadability curve and it is compared with the original loadability curve.

Effects of the following system and line design parameters on the transmission line loadability have been studied:

1. Voltage increase at the sending end.
2. Power angle.
3. Series compensation.
4. Shunt compensation.
5. Bundled conductors:
   - (i) Number of conductors in a bundle
   - (ii) Intra-bundle spacing
   - (iii) Phase separation
   - (iv) Conductor size.

To observe the effect of these parameters, a set of curves for each system parameter is produced. These curves are then compared with the analytical loadability curve. Based on these comparisons, general conclusions are drawn for the use by planning engineer.

CHAPTER TWO

INTRODUCTION TO TRANSMISSION LINE THEORY

In this chapter, basic fundamentals of electric transmission lines are discussed. A lossless line is assumed and expressions for voltage and current distribution on the line are derived. The effect of line termination on the voltage and current distribution is discussed. A criterion for the transmission line loadability is established.

2.1 Long Transmission Lines

The conductors of the line have series resistance and inductance in every unit length of the line. There is also a capacitance from conductor to conductor and to ground in every unit length of the line. Current at one end of a short section of the line differs from current at the other end as some current is shunted through the capacitance between phase and neutral. Voltage at one end of the section also differs from voltage at the other end due to inductance and resistance of the line.

The distributed inductance, resistance, capacitance, and conductance of a long transmission line can be represented by a series of small lumped elements. Figure 2.1.1 shows a transmission line represented by a number of series impedances and shunt capacitances connected in a ladder network. The line is assumed to be carrying steady-state and sinusoidal

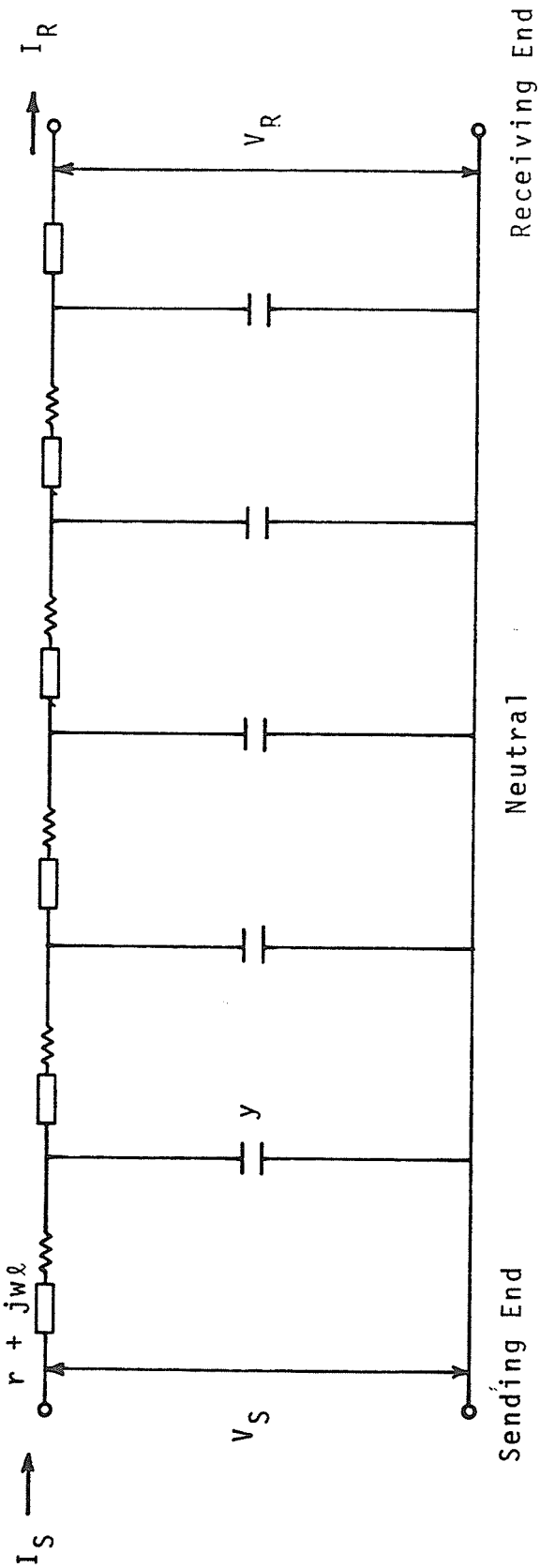


Figure 2.1.1: Representation of Single Phase of a long Transmission Line.

current and voltage. Line constants are assumed to be independent of current, voltage and time.

The average change of voltage and current per unit length of the line are proportional to current and voltage between conductors[9] respectively. These are expressed as

$$\frac{dV}{dx} = zI \tag{2.1}$$

and

$$\frac{dI}{dx} = yV \ . \tag{2.2}$$

The impedance and admittance per unit length of the line respectively are

$$z = r + j\ \omega\ell \tag{2.3}$$

and

$$y = g + j\ \omega c \tag{2.4}$$

where

r, ℓ, g and c are resistance, inductance, conductance and susceptance per unit length of the line respectively.

For higher voltage level transmission lines, bundled conductors are used. The resistance per unit length of the line is negligible as compared to the reactance per unit length. Figure 2.1.2 shows a plot of the ratio of resistance and reactance with the number of conductors in a bundle and voltage

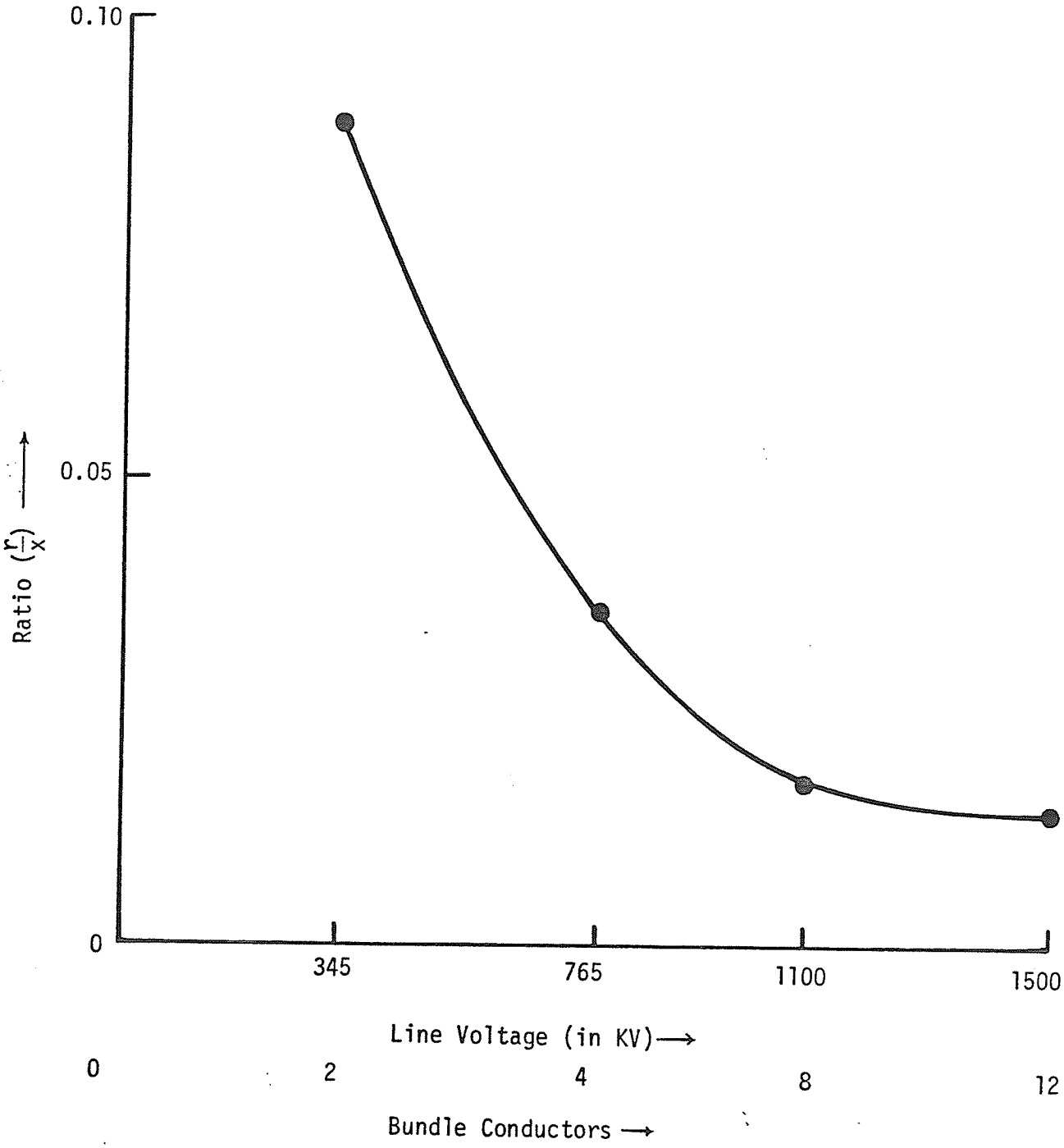


Figure 2.1.2: Resistance and Reactance Ratio Vs Number of Conductors and/or Line Voltage of Transmission Line.

level of transmission. It can be seen that with the higher number of conductors in a bundle or with higher voltage lines the ratio r/x is decreasing. For a 1500 KV transmission line with a 12 conductor bundle, this ratio is approx.0.0145. Hence, it is reasonable to assume the resistance of the line equal to zero. The conductance at 60 hertz is always neglected thus the line is assumed to be a lossless line.

By differentiating, the solution of equations (2.1) and (2.2) is

$$\frac{d^2V}{dx^2} = z\,\frac{dI}{dx} = zyV \qquad (2.5)$$

and

$$\frac{d^2I}{dx^2} = y\,\frac{dV}{dx} = zyI \quad . \qquad (2.6)$$

The solution of equations (2.5) and (2.6) gives voltage and current at any point along the line as

$$V = V_1\, e^{(zy)^{\frac{1}{2}}} + V_2\, e^{-(zy)^{\frac{1}{2}}x} \qquad (2.7)$$

and

$$I = I_1\, e^{(zy)^{\frac{1}{2}}x} + I_2\, e^{-(zy)^{\frac{1}{2}}x} \qquad (2.8)$$

where V_1, V_2 and I_i, I_2 are voltage and current components respectively.

x is the distance from the receiving end.
The propagation constant of the line is given by

$$\gamma = (zy)^{\frac{1}{2}} = \alpha + j\beta \qquad (2.9)$$

where

α is the attenuation constant; and,

β is the phase constant.

Equations for voltage and current can then be written as

$$V = V_1 e^{\alpha x} e^{j\beta x} + V_2 e^{-\alpha x} e^{-j\beta x} \qquad (2.10)$$

$$I = I_1 e^{\alpha x} e^{j\beta x} + I_2 e^{-\alpha x} e^{-j\beta x} . \qquad (2.11)$$

The attenuation constant is zero for the lossless line. Equations for voltage and current are then:

$$V = V_1 e^{j\beta x} + V_2 e^{-j\beta x} \qquad (2.12)$$

and

$$I = I_1 e^{j\beta x} + I_2 e^{-j\beta x} . \qquad (2.13)$$

At the receiving end x is equal to zero. Voltage and current at the receiving end, from equations (2.12) and (2.13) are:

$$V_R = V_1 + V_2 \qquad (2.14)$$

$$I_R = I_1 + I_2 . \qquad (2.15)$$

It is possible[9] to show that

$$V_1 = I_1 Z_c \tag{2.16}$$

and

$$V_2 = -I_2 Z_c \tag{2.17}$$

where

Z_c is the characteristic impedance of the transmission line.

For a lossless line, the characteristic impedance is

$$Z_c = \left(\frac{z}{y}\right)^{\frac{1}{2}} = \left(\frac{j\omega\ell}{j\omega c}\right)^{\frac{1}{2}} = \left(\frac{\ell}{c}\right)^{\frac{1}{2}} = (X_L\ X_c)^{\frac{1}{2}} \tag{2.18}$$

where

X_L is the inductive reactance of the line.

X_c is the capacitive reactance of the line.

2.2 Traveling Wave Theory

From the above discussion, it can be seen that both current and voltage on the transmission line are the sum of two components each respectively. These components act as two travelling waves. These waves produce lagging voltage or current at each point as they travel along the transmission line.

The negative sign in equation (2.17) shows that the two waves travel in opposite directions. One wave travels from the generator toward the load and is called the incident wave. The other wave travels from the load toward the generator and is called the reflected wave.

The incident wave brings energy from the generator to the load. The rate at which the load absorbs energy is determined by the load impedance. When the load impedance is unable to absorb energy, the rejected energy flows toward the generator in the form of the reflected wave.

The electrical behaviour of a transmission line can thus be described in terms of two traveling waves. Voltage and current components in each wave are related to each other by the characteristic impedance of the line. The relationship of the reflected wave to the incident wave at every point of the line is determined by the nature of the load. Thus, the voltage and current on the transmission line are determined in terms of receiving end impedance.

The receiving end impedance of the line is

$$\frac{V_R}{I_R} = Z_R \quad . \tag{2.19}$$

The voltage and current anywhere along the line in terms of receiving end quantities are calculated from equations (2.12 - 2.17). The voltage and current anywhere on the

line expressed[9] in the receiving end quantities are

$$V = V_R \cos\beta x + j\, I_R\, Z_c \sin\beta x \qquad (2.20)$$

$$I = I_R \cos\beta x + j\, \frac{V_R}{Z_c} \sin\beta x \quad . \qquad (2.21)$$

The voltage and current anywhere along the line in the hyperbolic functions are given by[19]

$$V = V_R \cosh\beta x + I_R\, Z_c \sinh j\beta x \qquad (2.22)$$

$$I = I_R \cosh\beta x + \frac{V_R}{Z_c} \sinh j\beta x \quad . \qquad (2.23)$$

At the sending end, the voltage and current are given by

$$V_s = V_R \cosh\beta\ell + I_R\, Z_c \sinh j\beta\ell \qquad (2.24)$$

and

$$I_s = I_R \cosh\beta\ell + \frac{V_R}{Z_c} \sinh\beta\ell \quad . \qquad (2.25)$$

where ℓ is the length of the line.

Equations (2.24) and (2.25) are solved to obtain the voltage and current at the receiving end,

$$V_R = V_s \cosh\beta\ell - I_s\, Z_c \sinh j\beta\ell \qquad (2.26)$$

and

$$I_R = I_s \cosh\beta\ell - \frac{V_s}{Z_c} \sinh j\beta\ell \qquad (2.27)$$

2.3 Wave Length and Phase Constant

The waves on the transmission line travel with a velocity of propagation and have wave length. The wave length is the distance between the points at which the alternating voltages (or currents) produced by the wave differ in phase by one complete cycle. Figure 2.3.1 shows the wave length of a transmission line.

Wave length is expressed as

$$\lambda = \frac{2\pi}{\beta} \quad . \tag{2.26}$$

A wave travels one wave length in the time of one cycle. It travels as many wave lengths in a second as there are cycles in a second. The velocity at which the wave travels is given by

$$v_p = \lambda f = \frac{2\pi f}{\beta} = \frac{\omega}{\beta} = \omega^2 \, (LC)^{\frac{1}{2}} \quad . \tag{2.27}$$

On most overhead lines, the phase velocity is the speed of light[20]. From equation (2.27), phase constant is

$$\beta = \frac{\omega}{v_\ell} \tag{2.28}$$

where

v_ℓ is the speed of light and its experimental value[34] is 186,282 miles/sec.

Converting radians into degrees, the value of the phase constant from equation (2.28) is equal to 0.116 degrees per mile.

The value of β is affected only slightly[19] for different lines and can therefore, be assumed constant. The correspond-

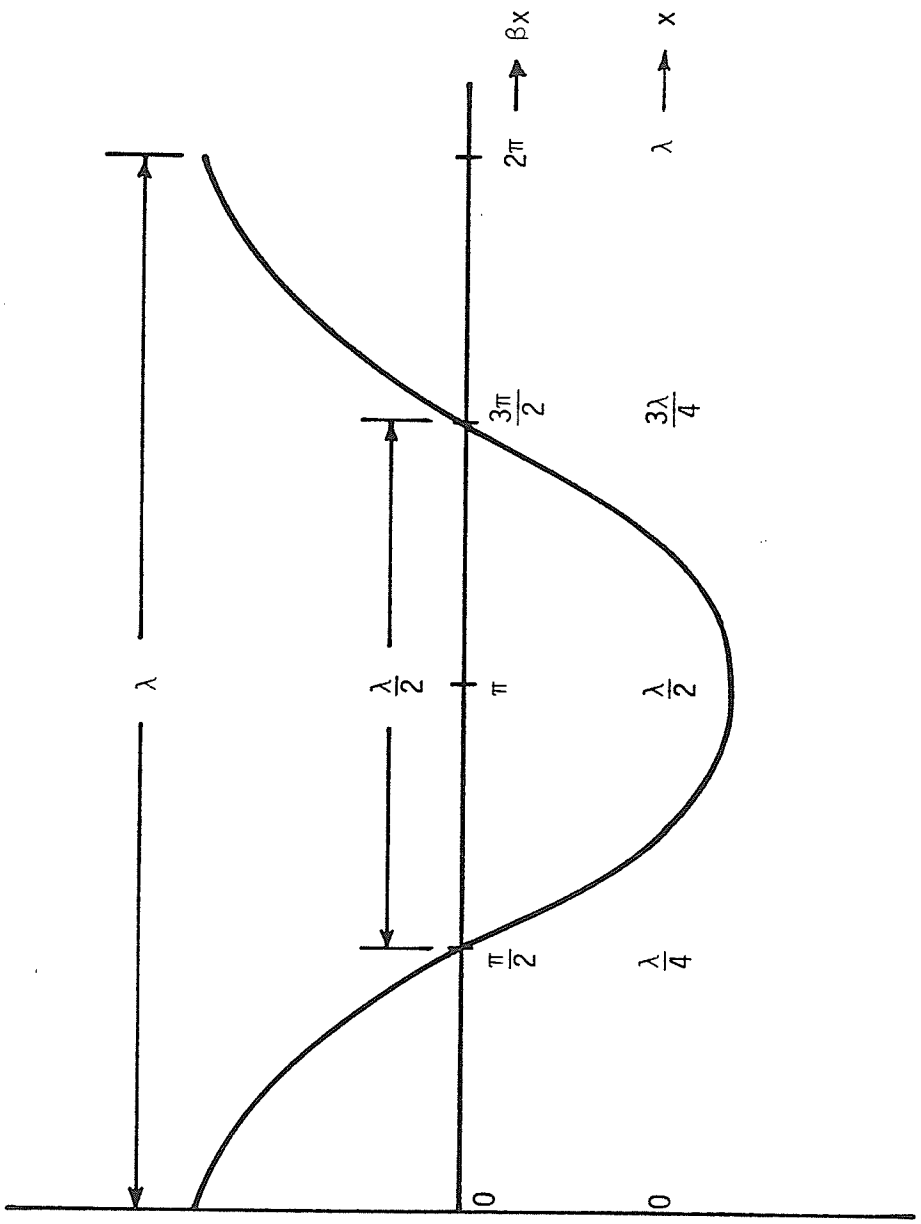


Figure 2.3.1: Wave Length.

ing value of wave length is 3,100 miles.

2.4 Effect of Line Termination on Voltage and Current Distribution on the Line

It was stated in Section 2.2 that computations of transmission line operation should begin with conditions of load at the receiving end. Various cases of load termination and their effects on the voltage and current distribution on the line are discussed here.

2.4.1 Open circuit termination

When the line is terminated in an open circuit, the receiving end impedance is infinite and the corresponding current is zero. The voltage and current on the line are then calculated by putting I_R equal to zero in equations (2.22) and (2.23),

$$V = V_R \cosh\beta\ell \tag{2.29}$$

$$I = \frac{V_R}{Z_c}\sinh j\beta\ell \quad . \tag{2.30}$$

Input impedance to the line is

$$Z_{so} = Z_c \coth\beta\ell = -j\, Z_c \cot\beta\ell \quad . \tag{2.31}$$

The voltage and current distribution on an open circuited line are shown in Figure 2.4.1. It can be seen that for

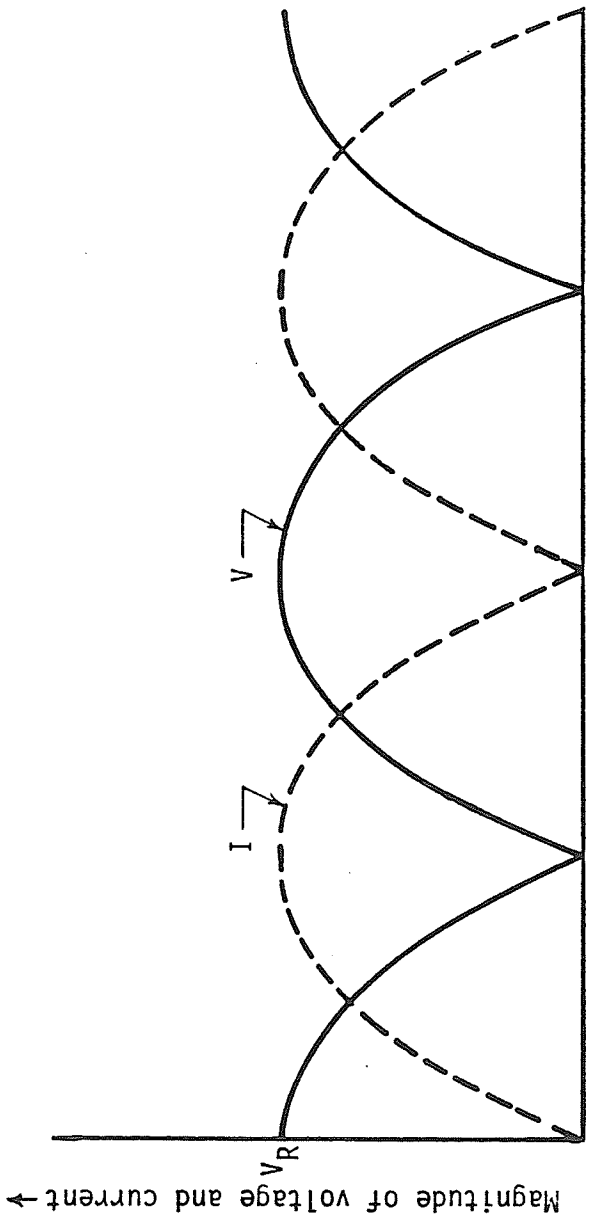


Figure 2.4.1: Voltage and Current Distribution on an Open-Circuited Line.

extra long distance transmission lines of about quarter-wave length long, the sending end voltage is less than the receiving end voltage.

It can be seen that voltage and current go to zero at alternate quarter-wave length points and are 90 degrees out of phase. At points where either current or voltage is zero, the transfer of power down the line is zero.

Figure 2.4.2 shows that when the transmission line length is less than the quarter-wave length, the input impedance is imaginary and negative. For more than quarter-wave length long lines, the input impedance is imaginary and positive. It is clear that there can be no transfer of power down the line.

2.4.2 Short circuited line

Zero voltage at the receiving end of a short-circuited line makes the receiving end impedance equal to zero. From equations (2.22) and (2.23), by putting V_R equal to zero, voltage and current on the line are given by

$$V = I_R Z_c \sinh j\beta\ell \qquad (2.32)$$

$$I = I_R \cosh\beta\ell \quad . \qquad (2.33)$$

The input impedance of the line is

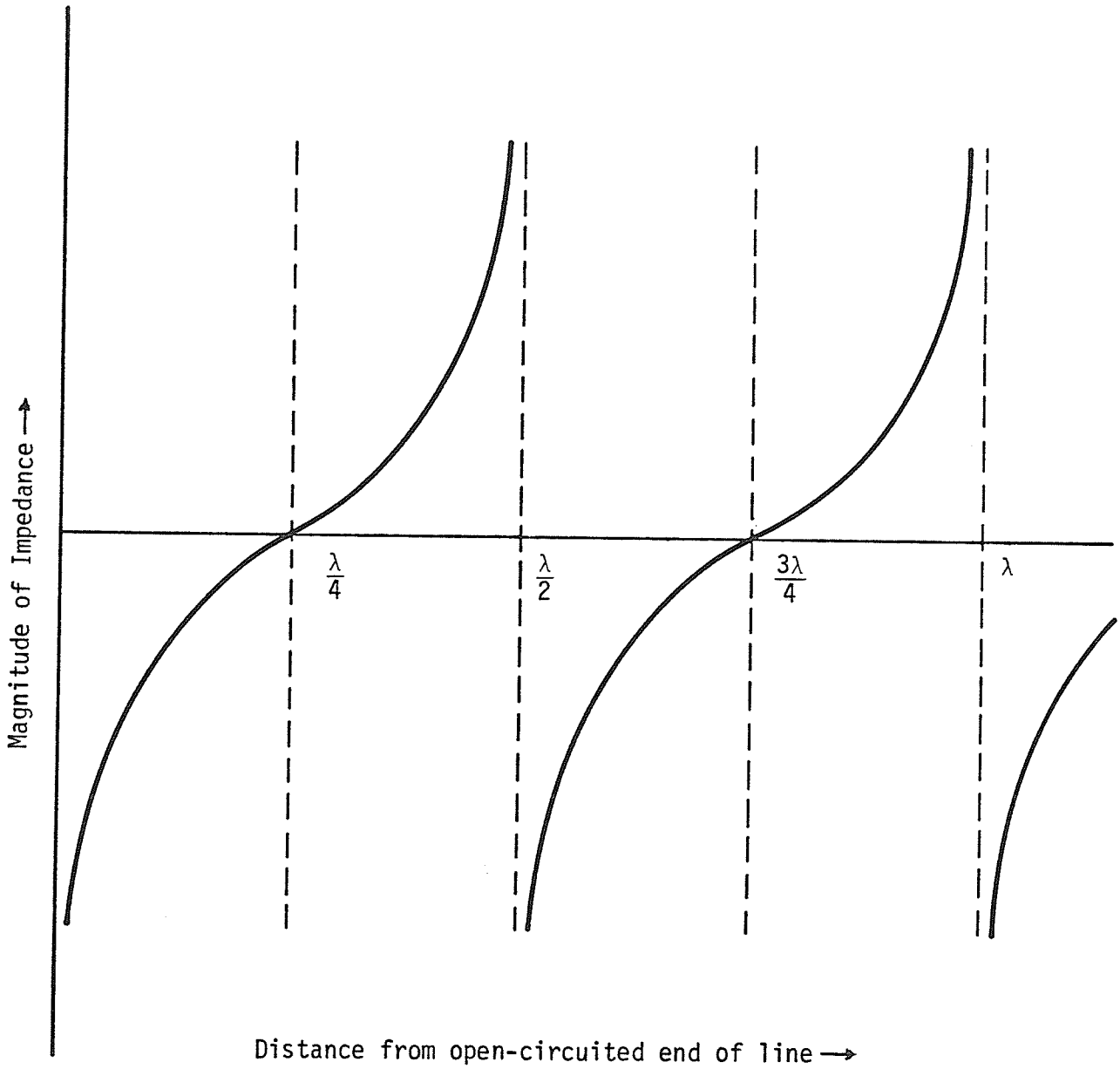


Figure 2.4.2: Magnitude of Input Impedance to the Open-Circuited Line.

$$Z_{ss} = Z_c \tanh \beta\ell = j\, Z_c \tan \beta\ell \quad . \qquad (2.34)$$

Figure 2.4.3 shows the voltage and current distribution on a short-circuited line. Voltage and current are in quadrature and the transfer of power down the line is not possible.

Figure 2.4.4 shows the magnitude of input impedance to the line. For line lengths of quarter-wave length and less the impedance is positive and power transfer is possible. The input impedance is imaginary in the second quarter-wave length and power transfer is unrealistic in this case.

2.4.3 Line terminated in characteristic impedance

When the load impedance is equal to the characteristic impedance of the line, the magnitude of the voltage and current are equal to the receiving end voltage and current magnitude (See Figure 2.4.5). Figure 2.4.6 shows the angles of voltage and current for different line lengths. Figures 2.4.7 and 2.4.8 show that the angle and magnitude of impedance is equal to the characteristic impedance all along the line. It is clear from above that the incident wave is entirely absorbed by the load, and energy loss due to the reflected wave is zero.

When the load is different from the characteristic impedance, the load is unable to absorb all the incident wave energy and some energy is rejected in the form of a reflected wave. Figures 2.4.9 and 2.4.10 show the voltage and current distribution on the line when the load impedance is greater and less than the characteristic impedance respectively.

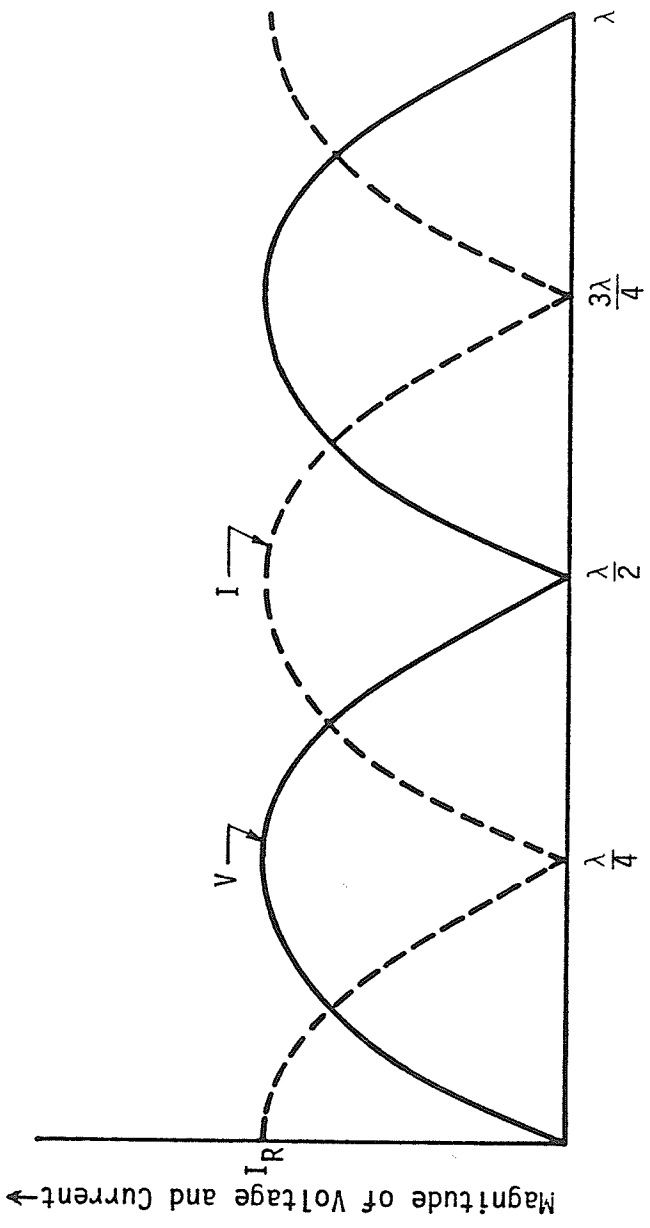


Figure 2.4.3: Voltage and Current Distribution on a Short-Circuited Line.

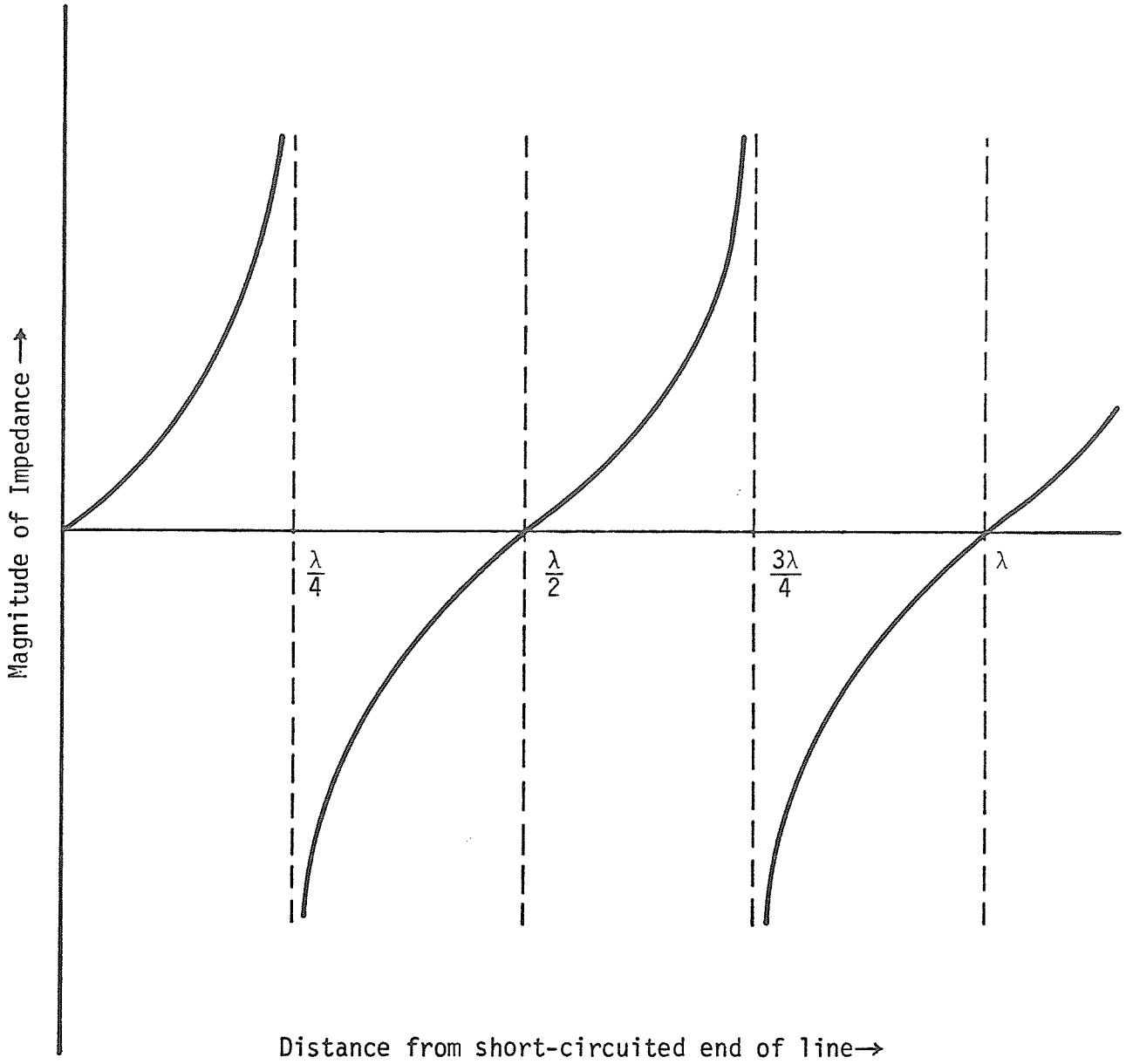


Figure 2.4.4: Magnitude of Input Impedance to Short-Circuited Line.

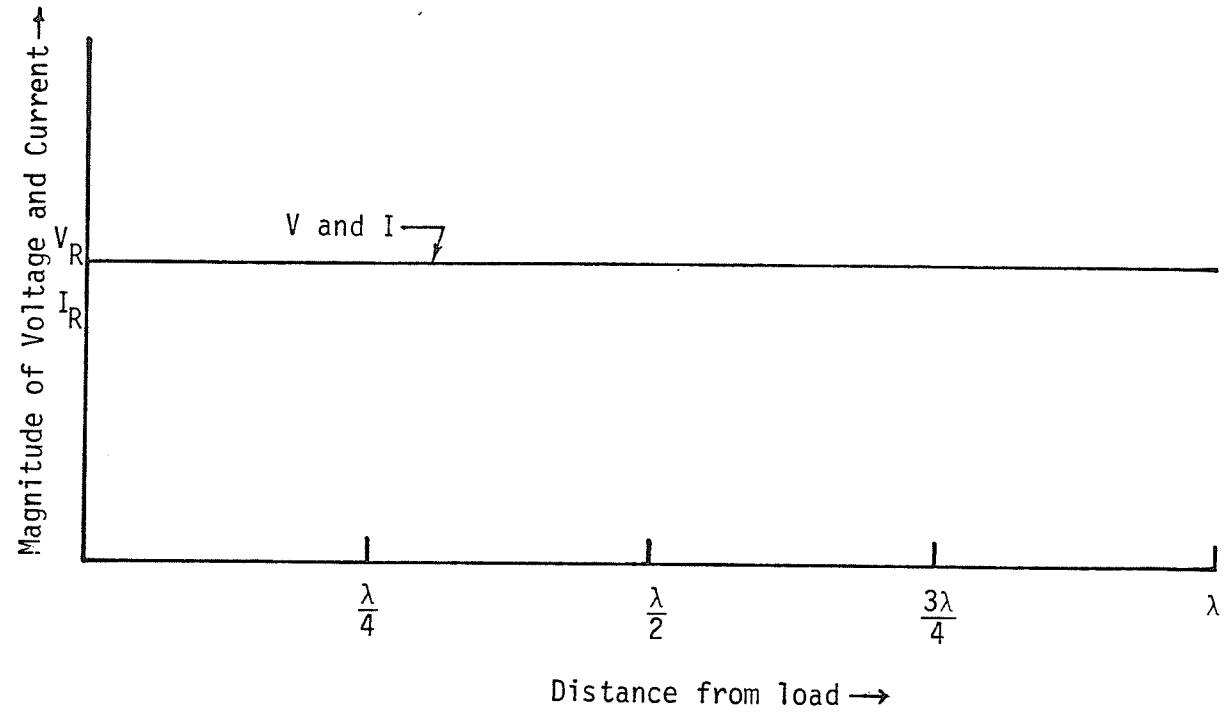


Figure 2.4.5: Voltage and Current Distribution on the Line Terminated with Characteristic Impedance.

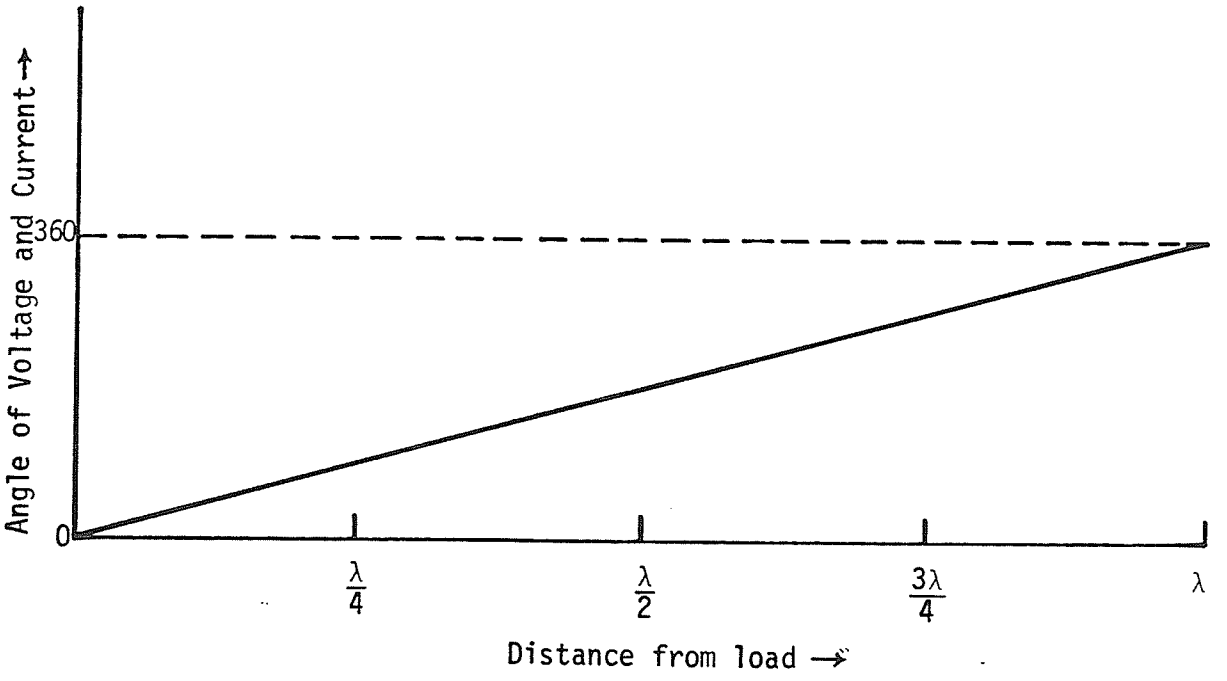


Figure 2.4.6: Angle of Voltage and Current Relative to Receiving End Quantities for the Line Terminated with Characteristic Impedance.

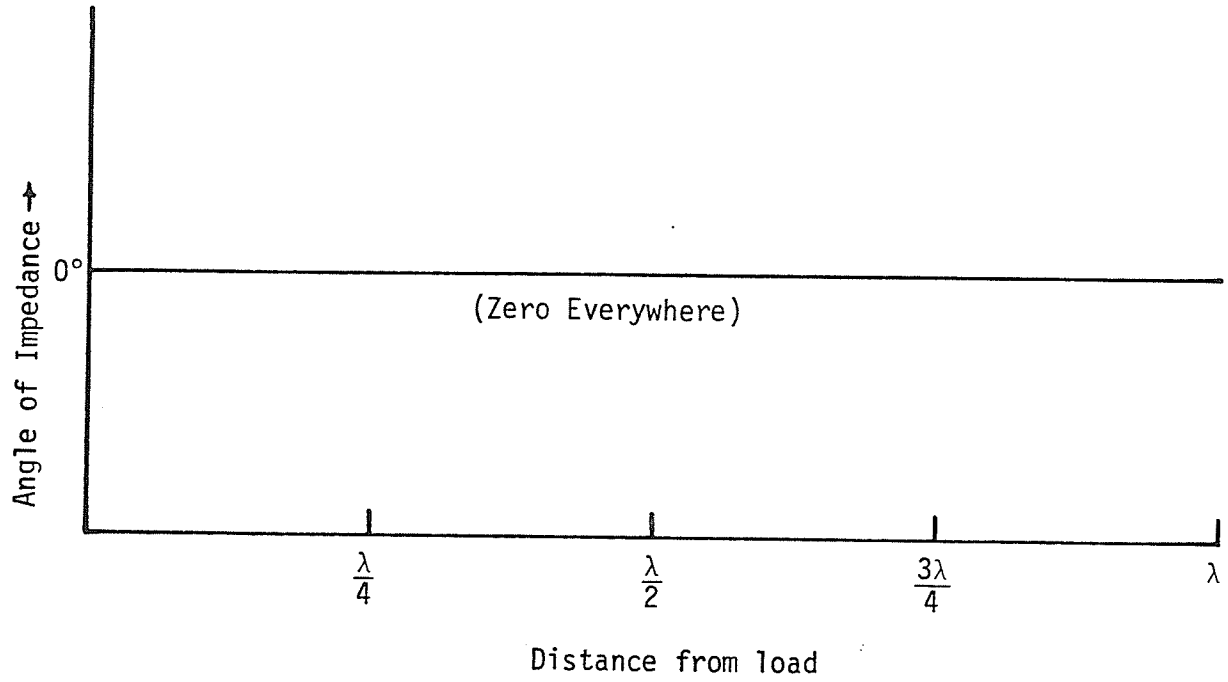


Figure 2.4.7: Angle of Impedance for the Line Terminated with Characteristic Impedance.

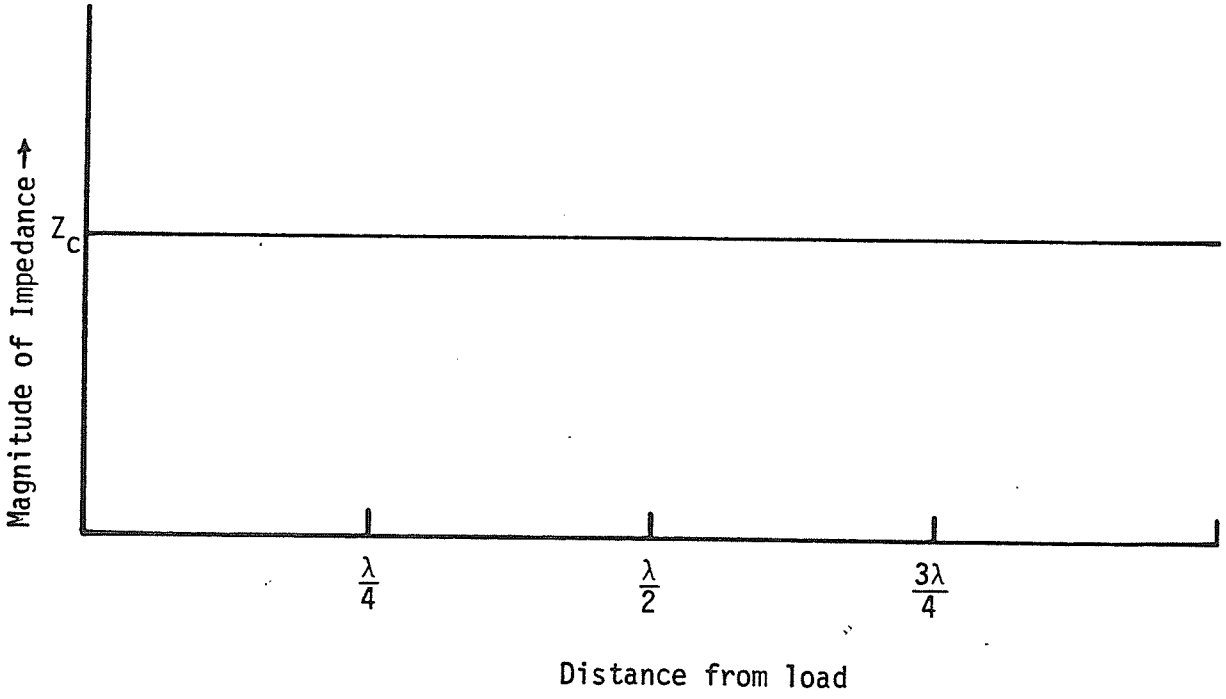


Figure 2.4.8: Magnitude of Impedance for the Line Terminated with Characteristic Impedance.

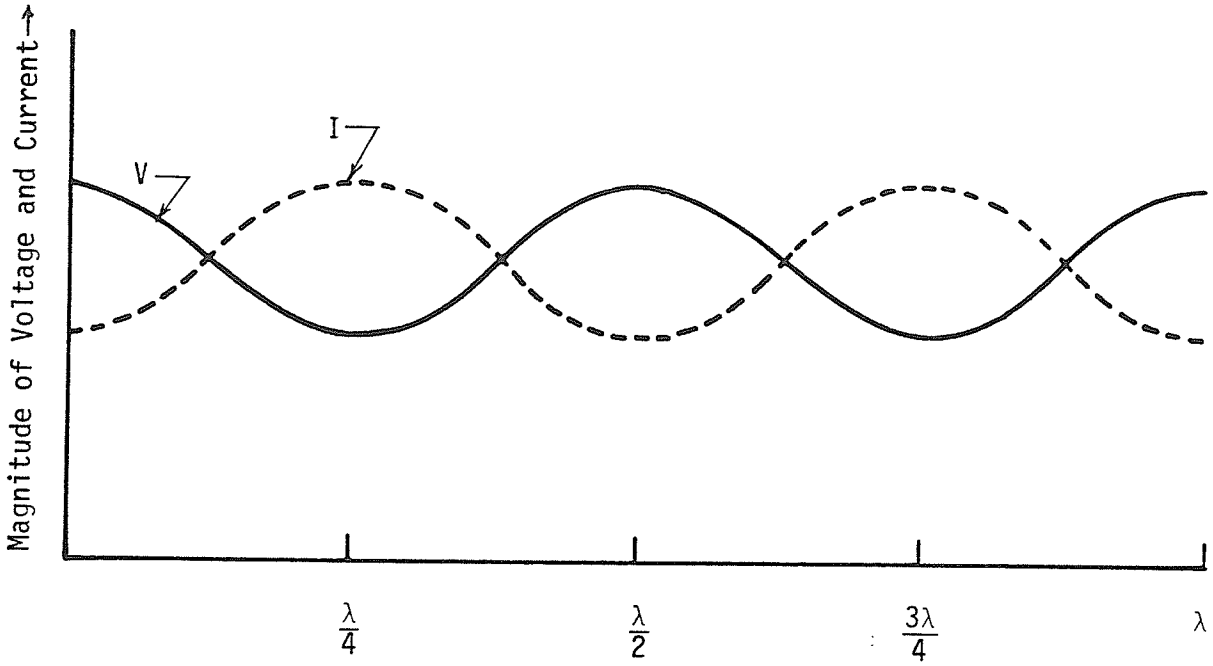


Figure 2.4.9: Voltage and Current Distribution on the Line with Higher Load Impedance than Characteristic Impedance.

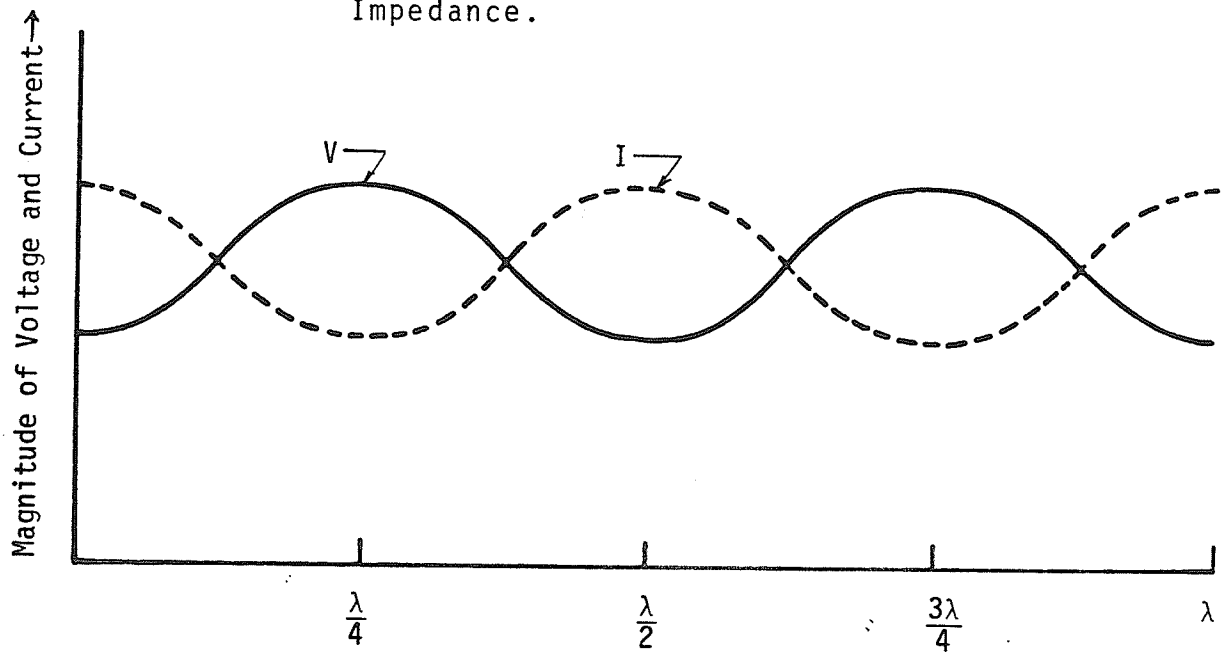


Figure 2.4.10: Voltage and Current Distribution on the Line with Lower Load Impedance than Characteristic Impedance.

load impedance is greater and less than the characteristic impedance respectively.

With the load impedance greater than the charactetistic impedance, the line behaves between the open circuit condition and the line load equal to the characteristic impedance condition When the load impedance is less than the characteristic impedance, the line behaviour is in between the short circuit and the line termination with the characteristic impedance.

It is clear from the preceding discussion that the ideal condition for the transmission of power down a line is when its load is equal to its characteristic impedance. In practical cases, the termination of the transmission line depends upon the amount of connected load.

2.5 Surge Impedance Loading

The load delivered over a line to a receiving end impedance which is equal to the characteristic impedance of the line, is called the Surge Impedance Loading.

The receiving end current of the line under these load conditions is

$$\bar{I}_R = \frac{\bar{V}_R}{\sqrt{3}} \cdot \frac{1}{Z_c} \quad . \qquad (2.35)$$

The bar on V_R and I_R denotes the corresponding

magnitudes of line to line voltage and current at the receiving end respectively.

It is stated in Section 2.4.3, that voltage and current are the same everywhere on the line when it is terminated with a load equal to its characteristic impedance. Thus, the Surge Impedance Loading (SIL),

$$SIL = \frac{\sqrt{3}\ \bar{V}_R\ \bar{V}_R}{\sqrt{3} \cdot Z_c} = \frac{(\bar{V}_R)^2}{Z_c} \quad . \qquad (2.36)$$

It is seen that the SIL is a natural consequence of the physical constants of the line and the choice of an operating voltage level at the receiving end. It can be used as a basis for comparison of loadability of transmission lines which have changed physical constants and are operating at different voltage levels.

It was also seen in Section 2.4.3, that the voltage and current peaks on a line are reduced due to the absence of the reflected wave when it is terminated with load equal to its characteristic impedance. The line insulation and energy losses become lower due to the reduced voltage and current on the line. Thus operation of a transmission line is most economical when it is terminated with a load equal to its characteristic impedance.

CHAPTER THREE

FACTORS AFFECTING LINE LOADABILITY

The transmission line loadability expressed as a per unit surge impedance loading and the criterion for natural loading were established in the previous chapter. In this chapter the standard loadability curve developed by St. Clair is discussed. The effect of various factors which limit and improve the transmission line loadability are discussed.

3.1 Standard Loadability Curve

Figure 3.1.1 shows the loadability of transmission lines in terms of their surge impedance loading for lengths up to approximately 400 miles. The curve as developed by St. Clair is based on practical considerations and experience. It assumes that the loadability varies directly as the square of the voltage^2. The curve has a 3.0 SIL at 50 miles and a 1.0 SIL at 300 miles as two bench-mark points. The 300 mile point considers that the stored inductive and capacitive energies that oscillate between the magnetic and electric fields of the line respectively are equal to each other at this point. Thus, lines of 300 mile length operate with very little or no reactive power supplied from either end of the transmission line.

At the 50 mile point the loadability is restricted by the thermal limitations of the conductors of the transmission

line. A 3.0 SIL loading at this point has been selected in the derivation of the loadability curve.

3.2 Factors Affecting Transmission Line Loadability

The loadability of transmission lines is limited and determined by a number of factors. Without limitations, the loadability of transmission lines is equal to their surge impedance loading, independent of line length and frequency of transmission. The factors affecting the loadability are discussed below:

3.2.1 Voltage level

Voltage level is the biggest factor in determining the loadability of the transmission lines. Table 3.1.1 shows different surge impedance loadings per circuit for different voltage levels. The plot of surge impedance loadings with corresponding voltages is shown in Figure 3.2.1. It can be seen that the loadability of the lines varies directly with the square of the voltage.

3.2.2 Stability

Stability is the most important limiting factor for longer lines[2] at any voltage level. The sending end voltage angle is advanced over the receiving end voltage to bring about flow of power over the line. Figure 3.2.2 shows that

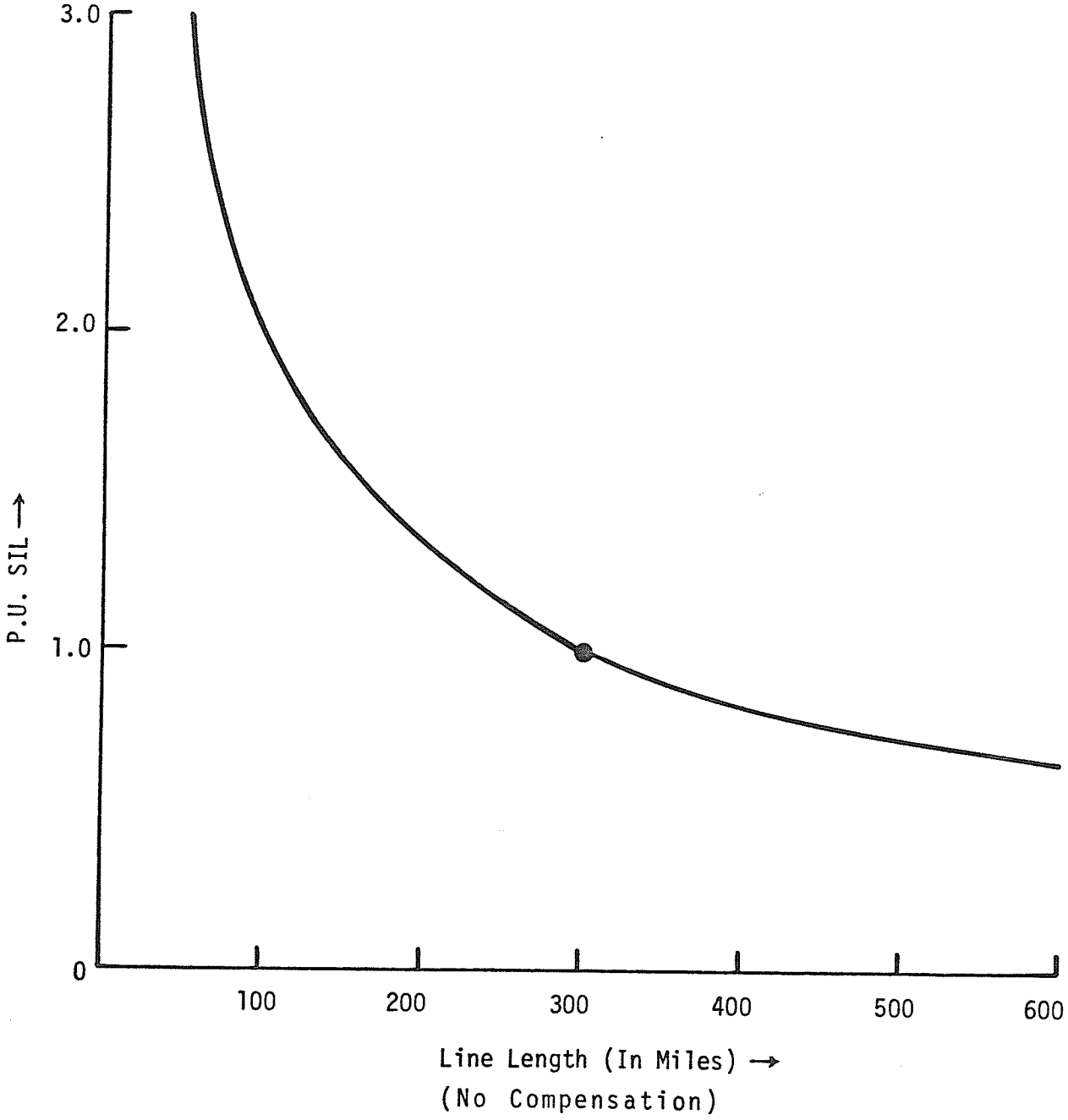


Figure 3.1.1: Original Standard Loadability Curve.

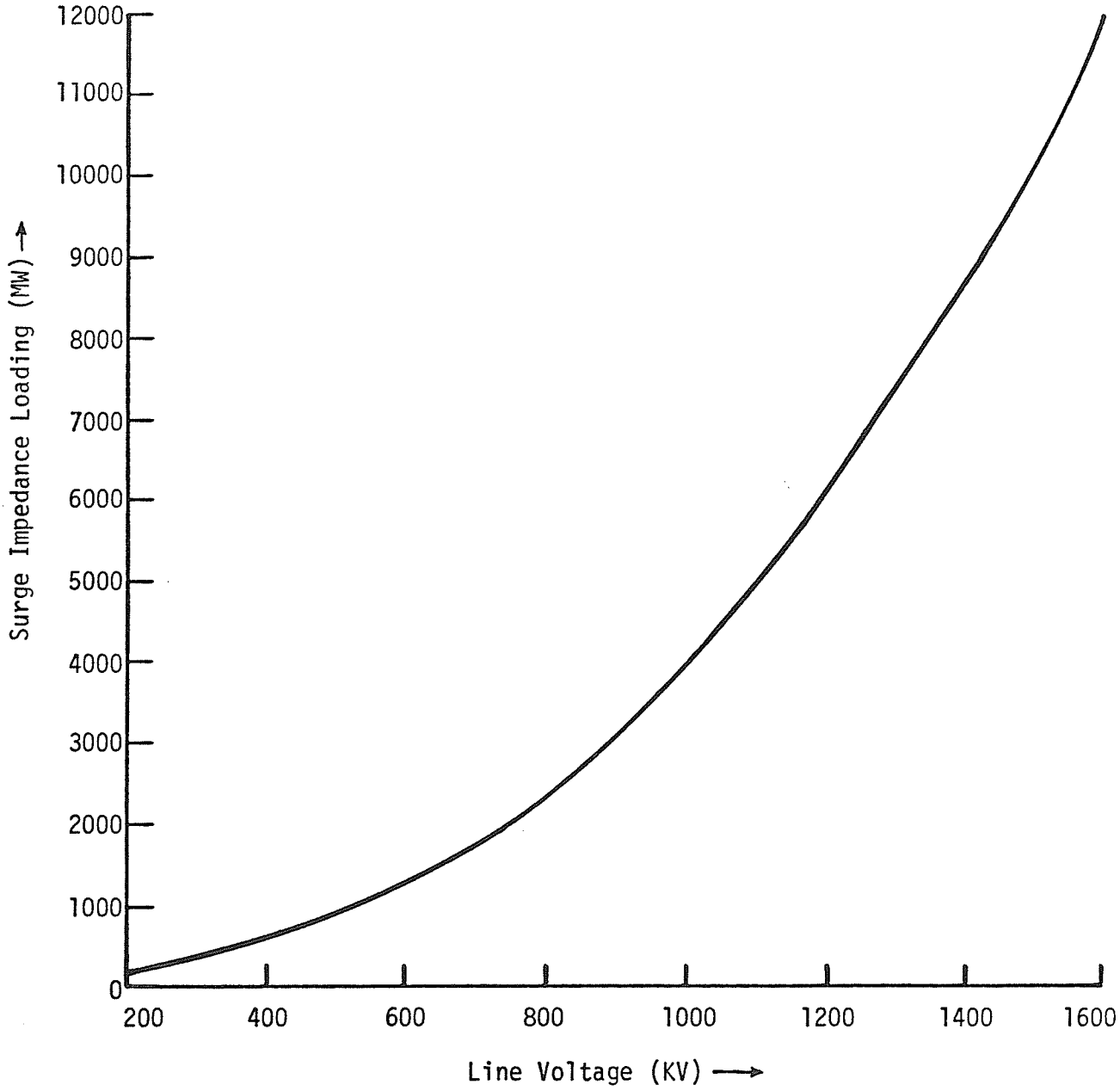


Figure 3.2.1: Typical Line Loadings Vs Voltage.

TABLE 3.1.1

SIL Per Circuit for Representative Voltage Levels in MW

Voltage Level (KV)	GMD (Δ equiv. spacing)	Single Conductor $Z_c \approx 400\Omega$	Two cond. Bundle $Z_c \approx 320\Omega$	Three Cond. Bundle $Z_c \approx 280\Omega$	Four Cond. Bundle $Z_c \approx 260\Omega$	Six Cond. Bundle $Z_c \approx 244\Omega$	Eight Cond. Bundle $Z_c \approx 223\Omega$	Twelve Cond. Bundle $Z_c \approx 200\ \Omega$
345	32'	295	372	425	455			
400	35'	400	500 or 530	570 or 595	615 or 640			
460	38'	530	662	756	815			
500	40'	625	780 or 820	890 or 910	960 or 985			
700	48'		1531	1750	1885	2168	2387	
765	53'			2047 $Z_c = 285\Omega$	2234 $Z_c = 262\Omega$	2522	2770	3187
1100	66'				4498 $Z_c = 269$	4936	5392	6149
1300	78'					6624	7209	8172
1500	86'					8618	9364	10581

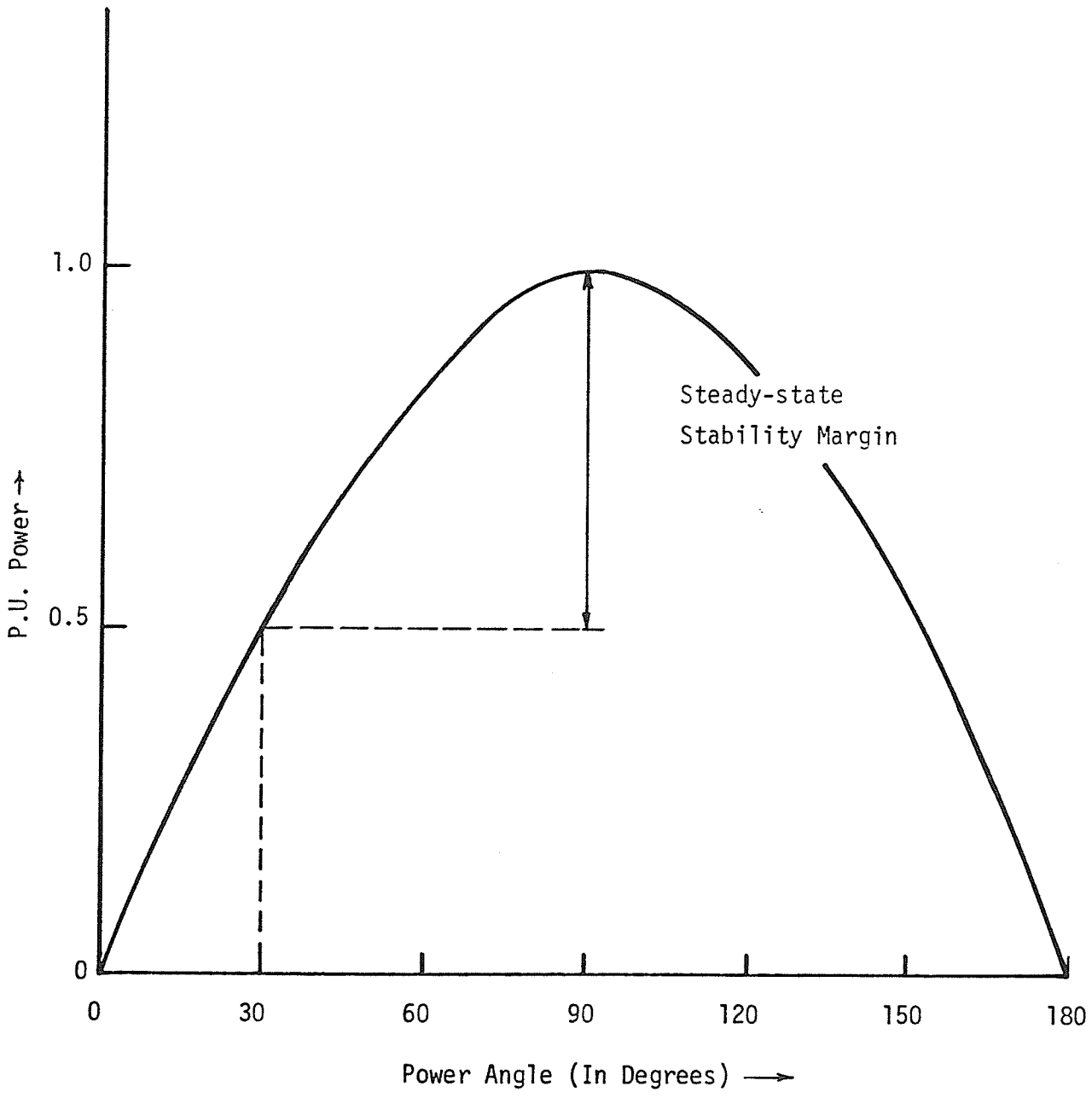


Figure 3.2.2: Power Angle Curve.

maximum transfer of power is possible when the difference of angle between the terminal voltages at the two ends of the line is 90 degrees. Without stability limitations, the economic transmission dictates heavier loadings per circuit with the increase in distance. For live loads or synchronous interconnections, the transmission system is required to develop upon major disturbances (such as faults) sufficient sychronizing torque to keep the connected synchronous machines in synchronism. When the system is maintained in the above stable conditions, severe limitations are imposed on the transmission line loadability with the increase in distance. For transmission of power over lines having synchronous terminal equipment, the limiting distance is about 300 miles at 60 cycles with a power angle of over 30 degrees. The operation of transmission lines is reasonable at a power angle of 30 degrees with a steady-state-stability margin of 50 percent[12]. When the terminal system reactances are taken into account the value of power angle higher than 30 degrees is possible.

3.2.3 Line Current

Line current rises directly with the voltage level and requires larger conductivity. Large size conductors are required to avoid corona at EHV and UHV levels and provide the larger conductivity required for the increased current. The increased transmission line loadability available with higher voltage levels is not restricted by the line current. But, it is an important factor for consideration of I^2R and I^2X_L losses.

3.2.4 Resistance losses

Resistance losses increase with the rise in current and are controlled within limits by the size of conductor. These losses are important for the selection of the conductor(s) size but are not a limiting factor in the line loadability.

3.2.5 Temperature rise

The temperature rise in line conductors is a critical problem in the case of short lines at lower voltage levels when these are heavily loaded. The line terminating equipment, such as wave-traps and sub-station equipment have their thermal limits as well. These restrict the amount of power flow through the line. At extra high voltage levels, the thermal capability of the line conductors exceeds the network requirements for the transfer of power through the line. Thus for EHV/UHV levels, temperature rise does not create a serious limitation on the transmission line loadability.

3.2.6 Net reactive losses

The operation of the line is possible under the following conditions with variable loads:

(i) Natural or surge impedance load.

(ii) Load greater than natural load.

(iii) Load less than natural load.

Net reactive loss is zero when the line is carrying a

natural load, Reactive losses increase and limit the loadability of shorter lines under heavy load conditions. Net reactive power is resulting from the lines operating under light load conditions but does not cause limitation to the line loadability.

3.2.7 Transmission distance

The series inductive reactance of the line increases with the increase in length of the line. It decreases the amount of power delivered over the line. The effect of increase in transmission line length on loadability can be seen in Figure 3.1.1.

3.2.8 Terminal system impedance

The combined reactance of step-up transformers and generators, as well as receiving systems reactances, add directly to the reactance of the line. The effect of system strength is significant on the utilization of inherent loadability of the line. At extra high voltage levels, with system strength not fully developed, the loadability of the line is limited considerably.

3.3 Methods for Overcoming Stability and Loading Limitations

With the increase in transmission distances, the transmission line cost becomes a greater part of total investment.

It is of economic importance to maintain or increase the circuit loading, to avoid the addition of extra transmission lines or higher voltage transmission levels. The economic line is achieved by optimization of stability and loading limitations. Following methods are considered for the above purpose:

3.3.1 Quadrature-boost transformers

The phase angular displacement between the sending and receiving end systems can be decreased with the use of quadrature-boost transformers. The method accomplishes this for a given load, but also decreases the angular displacement at which pull-out occurs. This results in no gain but a possible decrease in stability for the same line voltage.

3.3.2 Frequency changers

The loadability per circuit can be increased with frequency changers which produce lower frequency for the line. The drawback of lower frequency is that a line cannot be easily tapped and integrated into the system network as when operated at normal frequency.

3.3.3 Use of conversion equipment

Stability of very long distance lines is improved by the use of conversion equipment. An impedance equal to the surge impedance of the line is inserted at the receiving end,

thus improving the stability. The use of this method is limited to very long distance transmission lines of over 700 miles in length.

3.3.4 Tuned transmission lines

Tuned transmission lines operating at higher than normal frequencies are used to increase the transmission distance. The disadvantage of this method is the use of conversion equipment and a possibility of dangerous line voltages during fault conditions.

3.3.5 Use of cables

The limits of ac transmission are increased by the use of cables. The cables have inherently low reactance and allow a considerable increase in the distance to which the desired circuit loadings could be maintained.

High costs limit the use of cables only to some particular areas. Long distance transmission of power by cables depends upon the design of cables which can compete favourably in cost with the overhead line.

3.3.6 DC transmission

DC transmission can be and is used to transmit power. It increases the loadability considerably for the same voltage level and conductor size. The advantages of direct current

transmission over the alternating current increase with the increase in transmission distance. The disadvantage of dc transmission is the high cost of terminal equipment at both ends of the line. It is advantageous to use this type of transmission when the line cost is higher than the terminal equipment costs.

3.3.7 Use of series capacitor compensation

The inductive reactance of the transmission lines is the principal factor in limiting their loadability. This can be reduced by the following ways:

(i) Constructing an additional transmission line in parallel with the existing transmission line.

(ii) Inserting a series capacitor in the transmission line.

(iii) Removing a shunt reactor compensation off the transmission line.

(iv) Inserting a shunt capacitor in the transmission line.

The introduction of series capacitors on existing lines is less expensive than the addition of new lines[13]. Series capacitors are usually the economic solution with respect to both steady-state and transient stability[13, 14, 15, 16].

The inductive reactance of the line is reduced with the introduction of series capacitors. The reduced inductive reactance reduces the surge impedance and

hence the loadability of the line is increased. The transmission lines are compensated up to a certain degree of series compensation after which the gain in loadability is not economical as compared to cost of increased series compensation. The diminishing returns from higher degree of series compensation are caused by the increased I^2R losses accompanied with the higher loadability.

The location of series capacitors somewhat affect the loadability of the transmission lines. A suitable location for the placement of capacitors is at the middle of the line. Satisfactory operation is also possible when the capacitors are placed at the receiving end[17]. Series capacitors at the receiving end are advantageous for voltage regulation, although it increases the reactive power losses. To allow benefits of cost, operation and maintenance, the capacitors tend to be placed at either end of the line[18].

The optimization of the location of the series capacitors is a subject matter in itself and is not discussed in this dissertion. The series capacitors are assumed to be placed at either end of the transmission line for the analysis purposes.

3.3.8 Shunt-reactor compensation

Transmission lines operate at varying loads. Figure 3.3.1 shows the profile of the voltages when the line operates under different load conditions. The sending and

receiving end voltages are maintained at one per unit. Sudden load rejections cause the transmission line to operate at below the natural load and the line produces an excess of reactive power. This causes a voltage rise at the centre of the line (See no load curve, Figure 3.3.1) and results in corona, radio interference and higher insulation costs. The operation of transmission lines under heavy load conditions causes the voltage to sink at the middle of the line (See heavy load curve, Figure 3.3.1) and reactive power is consumed by the line.

The problems of over-voltage, corona, radio interference and voltage dip are related to the balance and flow of reactive power. Shunt reactor compensation is used to reduce the shunt susceptance and hold down over-voltages along the line. It consumes the reactive power that is required by the line under heavy loadings. Consequently, it is one of the major aspects of the shunt reactor compensation scheme to control reactive power flow during steady-state condition. It has to provide an optimum voltage profile of the system with respect to transmission losses and maintain voltage within the limits at each network bus.

The duty of reactive power compensation in EHV systems is to adjust the Var infeed in such a way that the active power loadability of long transmission lines is utilized to an optimum. The reactive compensation can be provided by the following means:

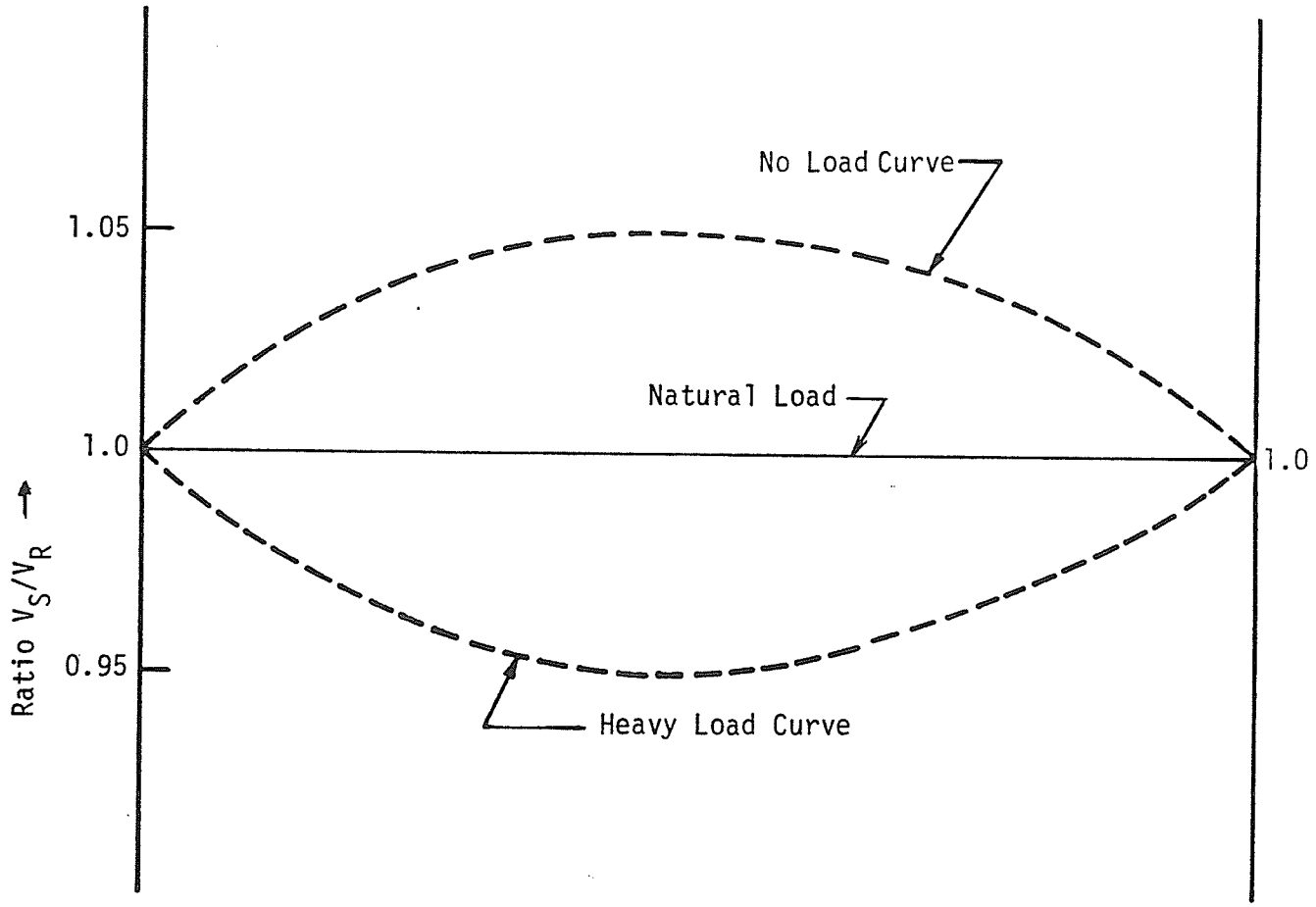


Figure 3.3.1: Voltage Profile of a Line under Various Load Conditions.

3.3.8.1 Rotating synchronous machines

Excitation control of a synchronous machine connected to the ac bus provides a controlled reactive power supply. The machines that are especially designed for the control of reactive power are known as synchronous compensators. In transmission networks synchronous compensators are used at the receiving ends of long transmission lines.

Typically a synchronous compensator when under-excited can absorb about half of its over-excited Var rating.

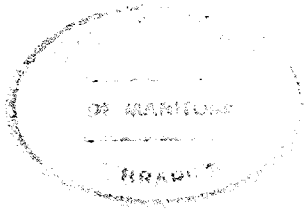
Unlike static devices, synchronous compensators have stored kinetic energy in their rotors. Hence it can exhibit transient oscillations of real power about a mean value of zero, during or following disturbances.

Also, the starting of such a machine can create a substantial voltage dip. When running, the synchronous compensator has its own stability problem in the event of a system fault due to its inertia.

The high capital investment, operating and maintenance costs and losses of a synchronous compensator add to its shortcomings.

3.3.8.2 Static compensators

Generally these type of shunt Var compensators do not



contribute to the system short circuit capacity, and have lower initial investment. They are less costly to operate and maintain compared to synchronous compensators.

Static compensators can be divided into two main classes according to their composite make up:

(a) Fixed elements; and,

(b) Controllable devices.

(a) Fixed Elements:

(i) Shunt capacitors

Shunt capacitor banks are used with mechanical switches to compensate the inductive reactive power at major load terminals in order to maintain the ac voltage at the rated value.

It may however lead to an excessive voltage rise on account of a sudden loss of load.

(ii) Linear shunt reactors

The inductance of these reactors is independent of their loading. They often are air-cored or gapped type reactors.

Permanently connected linear reactors are used to compensate the excessive capacitive power on long ac transmission lines. These suppress the voltage along the line and

its terminals under light load conditions.

Optimum line compensation requires shunt reactors to be switched out of service under heavy load transmission. This leaves the system open to transient over-voltages in case of a sudden loss of load. Also switching-in of the reactors causes an undesirable step voltage variation.

(iii) Saturable shunt reactors

The non-linear reactor is less effective in limiting instantaneous over-voltages, since a specific voltage-time area is required for changing the reactor magnetic state. Over-voltages are possible due to the partial shunt compensation not eliminating the Ferranti effect under light load conditions. This type of reactor, in conjunction with saturation effects of transformers, introduces some risk of sub-harmonic instabilities.

(iv) Gap connected shunt reactors

An arc gap is used to either switch a line shunt reactor in or out. The reactor assembly may take either form (a) or (b) as shown in Figure 3.3.2. The gaps are shunted by circuit breakers which are switched on by a trigger derived from the gap breakdown circuit. Gap connected reactors provide an economic but crude compensation means.

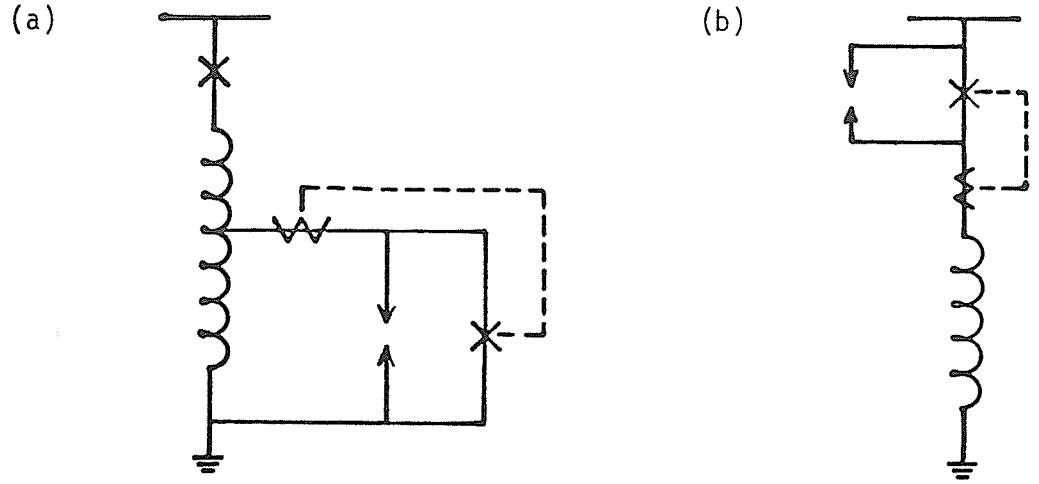


Figure 3.3.2: Gap Connected Reactors.

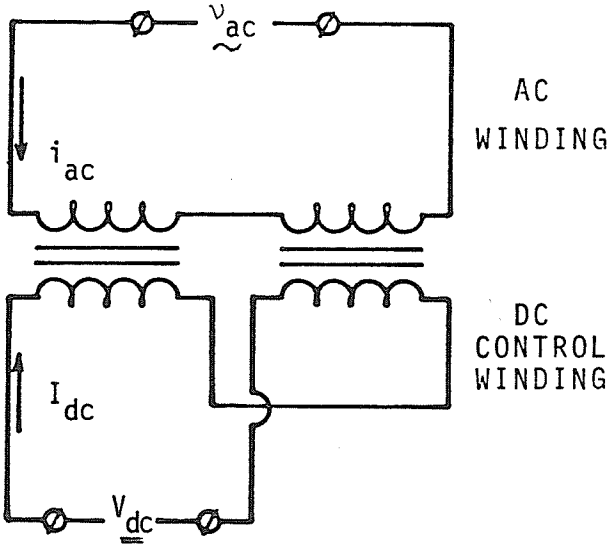


Figure 3.3.3: Transductors.

(b) Controllable Devices

(i) Transductors

A transductor is a reactor with direct current controlled saturation, i.e. the effective reactive impedance and the primary alternating current are controlled by a direct current fed into a separate winding (See Figure 3.3.3).

This type of controlled saturation compensators has the major drawback of slow response due to the dc circuit time constant and the dead time required to build up direct flux in the magnetic core.

Unfortunately, under system fault conditions the dc control winding is difficult to protect.

(ii) Thyristor-switched shunt reactors

Thyristor bridges are used as fast switches to connect a number of shunt reactors in small steps (Figure 3.3.4). The switching is preferred at voltage peaks to avoid dc current components being injected into the ac system. This form of discrete control requires a large number of components and hence increases the cost and deteriorates the reliability of the device.

(iii) Saturated reactors

The saturated reactor is designed to operate in the saturated region at normal operating voltages. With a

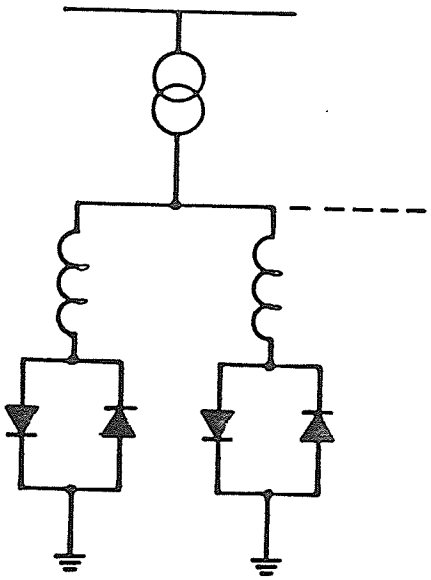


Figure 3.3.4: Thyristor-Switched Shunt Reactor.

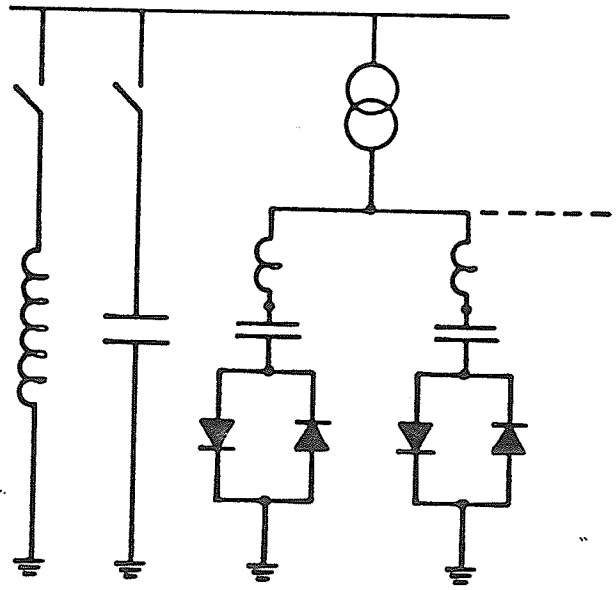


Figure 3.3.5: Thyristor-Switched Capacitor.

series and shunt capacitors combination it automatically varies the reactive power output and holds the terminal voltage constant. However, in application to weak ac systems, it causes high current harmonic content and ferroresonant sub-harmonic instability due to the presence of the slope correcting series capacitor.

(iv) Thyristor phase-controlled reactors

A smoother control of reactive power is achieved by using thyristor phase angle control of current through a linear reactor.

(v) Thyristor-switched capacitors

Thyristor-switched capacitors are also used as reactive power supply scheme as shown in Figure 3.3.5. This scheme has the drawback that the capacitors used are of the ac type which are less suitable for direct voltage but are subjected to dc voltage in the standby state. Provisions have to be made to repolarize them at regular intervals simulating a low frequency ac voltage, which complicates the control of thyristor bridges.

Generally, controlled static compensators are more suitable for reactive power flow. Regardless of the type of shunt compensators employed, the basic compensation principles are the same, requiring the generation of Vars

or induction of an appropriate voltage across the ac system impedance to regulate the terminal voltage. To restrict the insulation stresses caused by over-voltages following sudden load rejections, a part of the shunt reactive compensation is left permanently connected.

3.3.9 Use of bundled conductors

Bundled conductors are used to control, corona losses and radio interference at extra high voltages levels. It is stated in chapter one that the surge impedance loading depends on the constants of the line. Electrical characteristics of a transmission line change with the use of bundled conductors. Impedance and susceptance of phase conductors are important parameters in the transmission line design. The effect of bundled conductors on these parameters is studied here.

Inductive reactance of a transmission line is given by:

$$X_L = X_a + X_d \qquad (3.1)$$

where

X_a is the inductive reactance at a one foot spacing, and,

X_d is the inductive reactance spacing factor.

$$X_a = k_1 \log \left(\frac{1}{GMR}\right) \qquad (3.2)$$

where

k_1 is a constant equal to 0.2794

GMR is the mean radius of bundled phase and is given by

$$GMR = [N(GMR_c)(A)^{N-1}]^{\frac{1}{N}} \qquad (3.3)$$

N is the number of conductors in the bundle

GMR_c is the geometric mean radius of each sub-conductor

$$\text{Bundle radius } A = \frac{S}{2 \sin \frac{\pi}{N}} \qquad (3.4)$$

where

S is the distance between the sub-conductors

$$X_d = k_1 \log GMD_{line} \quad . \qquad (3.5)$$

The geometric mean distance of the line is the geometric mean of the distances between the phase conductor bundles.

Capacitive reactance of the transmission line is given by

$$X_c = X_a' + X_d' \qquad (3.6)$$

where

X_a' is the capacitive reactance at a one foot spacing,

and

X_d' is the capacitive reactance factor.

$$X_a' = k_2 \log \left(\frac{1}{r_B}\right) \tag{3.7}$$

where

k_2 is constant equal to 0.0683.

The effective radius of the bundled phase is

$$r_B = \left(N \cdot r_b \, A^{N-1}\right)^{\frac{1}{N}} \tag{3.8}$$

r_b is the actual radius of each conductor in a bundle.

$$X_d' = k_2 \log \left(GMD_{line}\right) . \tag{3.9}$$

It is clear that inductive and capacitive reactances of the line can be affected with a change in number of conductors in a bundles, phase separation, intra bundle spacing and conductor size. It changes the surge impedance of the transmission line and hence loadability is affected.

CHAPTER FOUR

TRANSMISSION LINE LOADABILITY CURVES

In this chapter, an analytical approach is made to co-ordinate surge impedance loading with voltage levels, power angle, active power, reactive power, complex power and system stability factors. Generalized expressions are derived for overhead lines with and without series-capacitor and shunt-reactor compensations. A generalized analytical method is presented as well. Effects of various sytem parameters on the transmission line loadability are analyzed and are documented in the form of graphs.

4.1 Representation of L-C Network

Figure 4.1.1 shows a power transfer network. Each phase of the transmission link between two points in the system is assumed to be a lossless four-terminal network connected between two source terminals. The receiving end voltage is assumed as a reference voltage with a zero angle.

The sending end power equations for the real and reactive power are given by[19]

$$P_S = \frac{V_S^2}{Z_{SS}} \cos\theta_{ss} - \frac{V_S V_R}{Z_{SR}} \cos\left(\theta_{SR} + S_{SR}\right) \qquad (4.1)$$

$$Q_S = \frac{V_S^2}{Z_{SS}} \sin\theta_{SS} - \frac{V_S V_R}{Z_{SR}} \sin\left(\theta_{SR} + \delta_{SR}\right) \qquad (4.2)$$

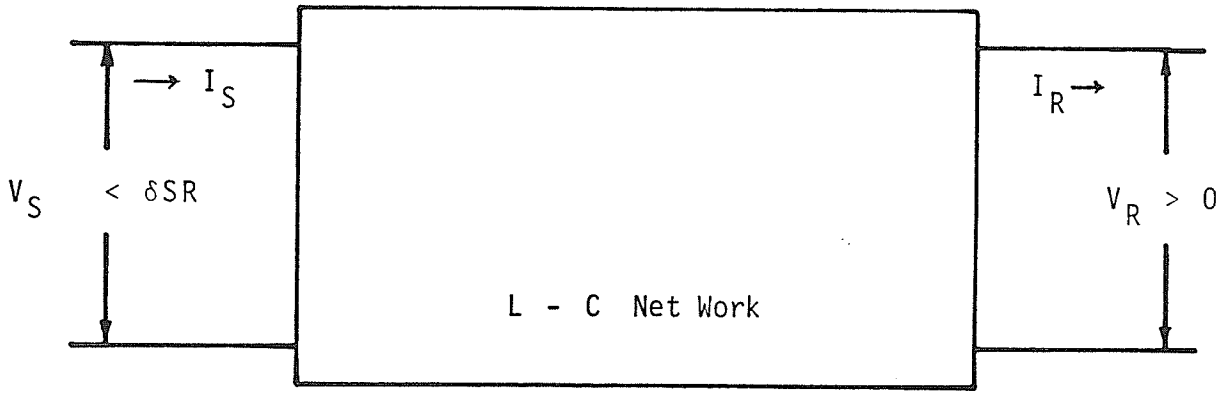


Figure 4.1.1: Power Transfer Network.

where

Z_{SS} is the sending end impedance with the receiving end short circuited and is given by equation (2.34).

Z_{SR} is the transfer impedance of the line.

θ_{SS} is the angle of the sending end impedance.

θ_{SR} is the angle of transfer impedance.

δ_{SR} is the power angle - difference of angles between the sending and receiving end voltages.

For a lossless line

$$\theta_{SR} = \theta_{SS} = 90° \ . \tag{4.3}$$

The transfer impedance of the line with the receiving end short-circuited from equation (2.24) is

$$\bar{Z}_{SR} = \left|\frac{\bar{V}_S}{\bar{I}_R}\right|_{V_R = 0} = Z_c \tanh j\beta\ell = jZ_c \tan\beta\ell \ . \tag{4.4}$$

The values of the sending end and transfer impedances from equations (2.34) and (4.4) are substituted in equations (4.1) and (4.2),

$$P_S = \frac{V_S V_R \ \mathrm{Sin}\delta_{SR}}{Z_c \ \mathrm{Sin}\beta\ell} \tag{4.5}$$

$$Q_S = \frac{V_S^2}{Z_c \tan\beta\ell} - \frac{V_S V_R \cos\delta_{SR}}{Z_c \sin\beta\ell} \quad . \qquad (4.6)$$

By putting the ratio of sending end voltage to receiving end voltage equal to n, the equations (4.5) and (4.6) become

$$P_S = \frac{n\, V_R^2 \,\mathrm{Sin}\delta_{SR}}{Z_c \,\mathrm{Sin}\beta\ell} \qquad (4.7)$$

$$Q_S = \frac{n\, V_R^2}{Z_c} \left(\frac{n}{\tan\beta\ell} - \frac{\cos\delta_{SR}}{\sin\beta\ell}\right) . \qquad (4.8)$$

Per unit surge impedance loading factors for active and reactive powers are calculated by dividing the equations (4.7) and (4.8) by the surge impedance of the line and substituting in for the value of β

$$P = \frac{n \sin\delta_{SR}}{\sin\ 0.116\ell} \qquad (4.9)$$

$$Q = n \left(\frac{n}{\tan\ 0.116\ell} - \frac{\cos\delta_{SR}}{\sin\ 0.116\ell}\right) . \qquad (4.10)$$

The transmission lines carry both active and reactive powers. The per unit surge impedance loading factor for complex

power carried by the line is

$$S = (P^2 + Q^2)^{\frac{1}{2}} = \frac{(P_S^{\,2} + Q_S^{\,2})^{\frac{1}{2}}}{SIL} \qquad (4.11)$$

or

$$S = \frac{n}{\text{Sin } 0.116\ell} \left[1 + n^2 \cos^2(0.116\ell) - 2n \cos\delta_{SR} \cos(0.116\ell)\right]^{\frac{1}{2}} . \qquad (4.12)$$

4.2 Expressions for Compensated Lines

In the previous chapter it was stated that extra high voltage lines are provided with series capacitor and shunt-reactor compensations. To derive the loadability curves for the compensated lines, expressions for both series and shunt compensation are derived.

Series capacitors reduce the inductive reactance of the line. With the distributed series compensation on the line, the amount of inductive reactance left in the line after series compensation is

$$X_L' = (1 - N_{SE})\, X_L \qquad (4.13)$$

where

N_{SE} is the percent series compensation expressed in decimal form.

The characteristic impedance and phase constant of the series compensated line are respectively,

$$Z_c' = \left[\frac{(1 - N_{SE})\ \omega L}{\omega c}\right]^{\frac{1}{2}} = (1 - N_{SE})^{\frac{1}{2}}\ Z_c \qquad (4.14)$$

and

$$\beta' = [(1 - N_{SE})\ \omega L \times \omega c]^{\frac{1}{2}} = [1 - N_{SE}]^{\frac{1}{2}}\ \beta\ . \qquad (4.15)$$

The shunt compensation reduces the capacitive susceptance of the line. With the distributed shunt compensation on the line, the net shunt capacitive susceptance after the shunt compensation is

$$X_c' = (1 - N_{SH})\ \omega c \qquad (4.16)$$

where

N_{SH} is the percent shunt compensation expressed in decimal form.

The characteristic impedance and phase constant of the shunt compensated line are respectively,

$$Z_c'' = \frac{\omega L}{(1 - N_{SH})^{\frac{1}{2}}\ \omega c} = \frac{Z_c}{(1 - N_{SH})^{\frac{1}{2}}} \qquad (4.17)$$

and

$$\beta'' = [\omega L\ (1 - N_{SH})\ \omega c]^{\frac{1}{2}} = (1 - N_{SH})^{\frac{1}{2}}\ \beta \quad . \qquad (4.18)$$

The expressions for the surge impedance loading factors for a series and shunt compensated line are calculated from equations (A.3), (A.5) and (A.7) (see Appendix A),

$$P' = \frac{n\ \mathrm{Sin}\delta_{SR}(1 - N_{SH})^{\frac{1}{2}}}{(1 - N_{SE})^{\frac{1}{2}}\ \mathrm{Sin}\ [\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\ 0.116\ell]} \qquad (4.19)$$

$$Q' = n \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right)^{\frac{1}{2}} \left[\frac{n\ \cos\ [\{(1 - N_{SE})(1 - N_{SH})^{\frac{1}{2}}\}\ 0.116x] - \cos\delta_{SR}}{\sin\ [\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\ 0.116\ell]}\right] \qquad (4.20)$$

and

$$S' = n \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right)^{\frac{1}{2}} \frac{\left[1 + n^2\cos^2[\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\ 0.116\ell] - 2n\ \cos\ [\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}} 0.116\ell]\ \cos\delta_{SR}\right]^{\frac{1}{2}}}{\sin\ [\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\ 0.116\ell]} \quad . \qquad (4.21)$$

4.3.1 Analytical loadability curves

To study the active and reactive power behaviour of the transmission line loadability, the surge impedance loading factors from equations (4.19 to 4.21) are plotted separately (See Figure 4.3.1), with power angle equal to 30 degrees. The transmission line length varies from 50 to 600 miles with equal voltages at the two ends of the line. The curves are plotted with no series-capacitor and shunt-reactor compensations.

4.3.2 Standard analytical loadability curve

For short lengths, the values of loadings given by the complex power loadability curve in Figure 4.3.1 are not practical due to thermal capabilities of the lines. Also, the reliability of the power supply is reduced with the lines operating at such heavy loadings. It can be seen from Figure 4.3.2 that loadability values can possibly decrease for shorter distances with the reduction in power angle. The value of 3.0 SIL is fixed in the analytical curve at a 50 mile length for the comparison of this curve with the standard curve. However, with the use of bundle conductors, it looks as though 4.0 p.u. SIL would be acceptable. The power angle is calculated to be equal to 15 degrees at the 50 miles point for a 3.0 SIL loadability. The variable power angle curve x'yz' is plotted with a gradual increase in

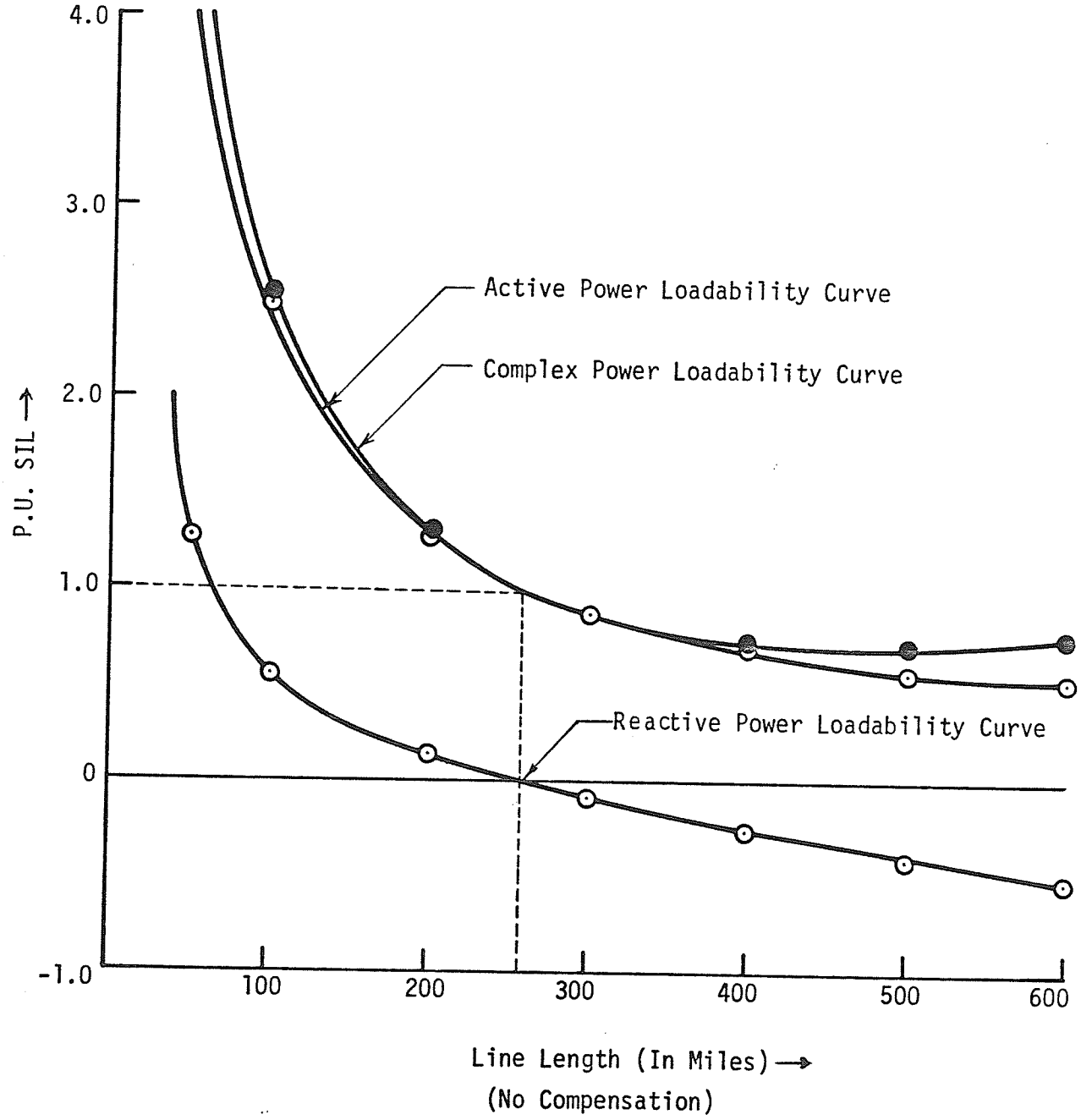


Figure 4.3.1: Analytical Loadability Curves.

the power angle from 15 degrees at 50 miles to 60 degrees to 600 miles with the voltage ratio maintained equal to unity. (See Figure 4.3.2). The constant power angle curve xyz is the complex loadability curve from Figure 4.3.1 with a constant power angle of 30 degrees. The portions x'y and yz of these curves are joined and the standard analytical loadability curve is plotted as shown in Figure 4.3.2.

4.4 System Studied

The transmission line assumed for the study has constants as shown in Table 4.1.

TABLE 4.1

Base Quantities	
Base Power	11,150 MVA
Base Voltage	1,500 KV (L-L)
Base Impedance	200 Ω
Line Construction	
(50 - 600) miles, Flat Tower configuration, 12 Conductor bundle	
Line Spacing	
Phase-to-Phase =	68.5 feet

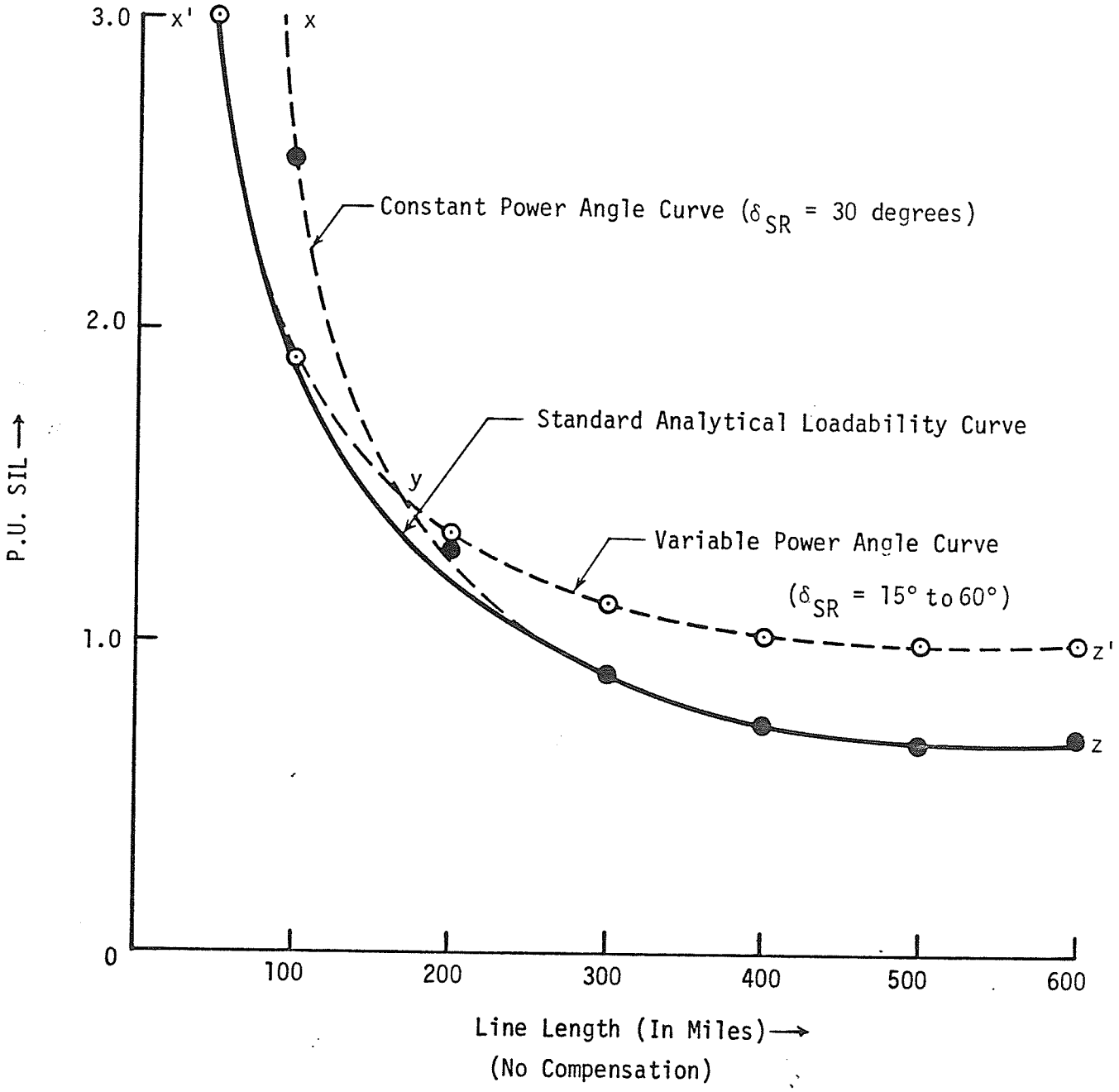


Figure 4.3.2: Standard Analytical Loadability Curve.

Conductor:

1781 MCM, ACSR, 84/19.

A base case with parameters shown in the Table 4.4.1 was studied. A number of cases were studied by varying the magnitude of the parameters of the base case.

TABLE 4.4.1

Transmission Line Length	Varying from 50 - 600 Miles
Phase separation	68.5 feet
V_S, V_R	1.0 P.U.
δ_{SR}	30 degrees
N_{SE}	0 percent
N_{SH}	0 percent
N	12
S	14 inches

The effects of variation of these parameters are indicated by different sets of graphs.

4.5 Variation of Voltage Ratio

In a transmission line operation under varying load conditions, the voltage ratio can be expected to vary within the ($\pm$5 percent) allowed limits due to the response time of the compensating schemes. An increase in the voltage at the sending end increases the voltage ratio more than unity and hence the loadability of the line increases.

Figure 4.5.1 shows a set of loadability curves with voltage rise of 3 percent and 5 percent at the receiving end. The curves for 2 and 4 percent are purposely not drawn to more clearly distinguish the various curves from the base curve of 0 percent change.

4.6 Variation of Power Angle

A power angle of 30 degrees is reasonable for stable operation of a long transmission line network. A variation

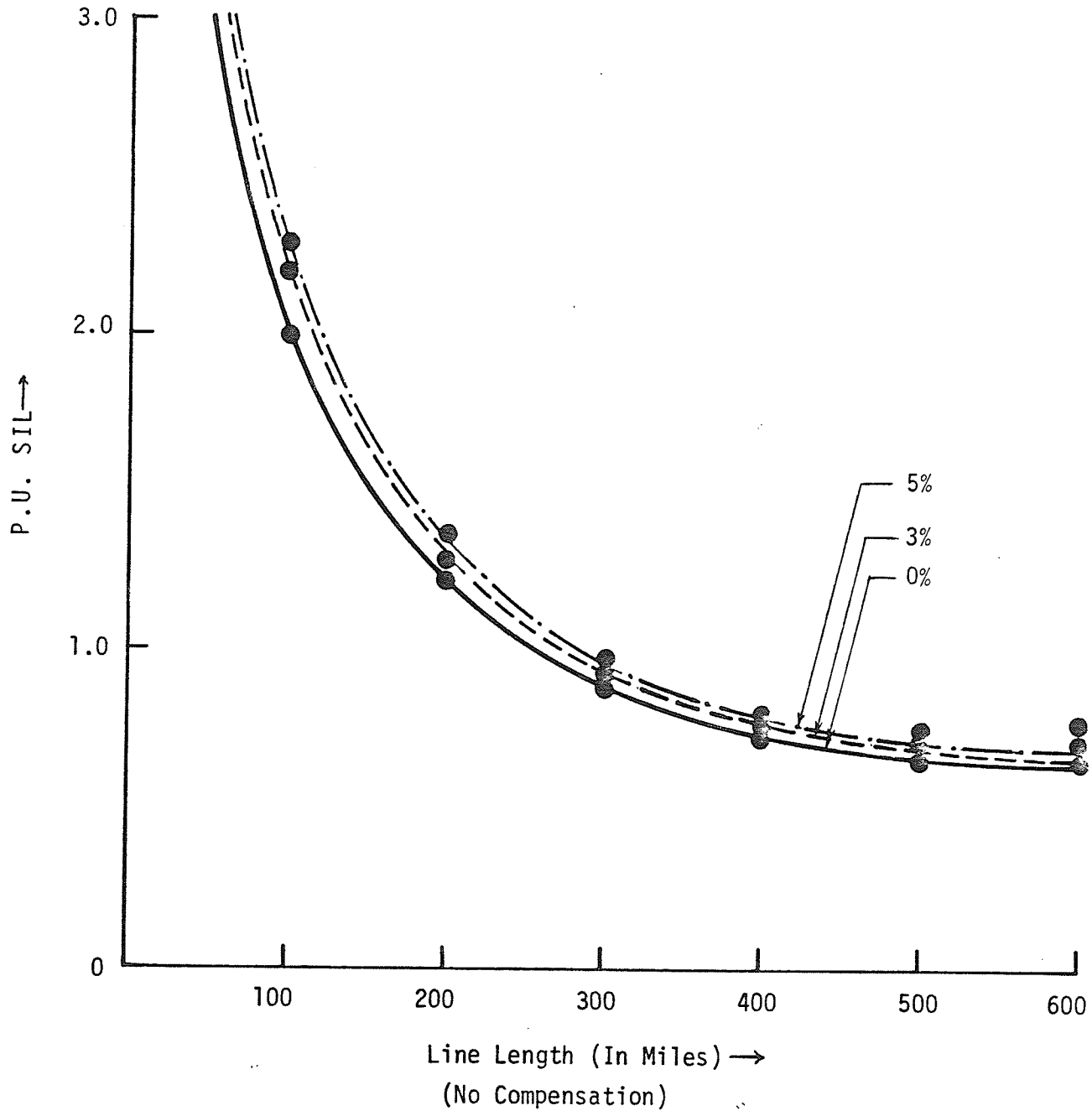


Figure 4.5.1: Effect of Voltage Increase at Sending End on Line Loadability.

in power angle is possible due to response times of protection and compensating schemes for clearing the fault and voltage stabilization, respectively, due to sudden load rejections and faults.

To study the transmission line behaviour, operating at different power angles, a set of curves is obtained with power angle varying from 20 degrees to 60 degrees. (See Figure 4.6.1). The voltage ratio is maintained equal to unity.

4.7 Variation of Compensation

It was stated in Chapter Three that long transmission lines have to be provided with both series and shunt compensations or static compensator. Series compensation reduces the inductance of the line and increases the load-ability of the lines. Reactive power flow of the line is controlled by the shunt compensation. The effect of variation of series and shunt compensations on the line loadability is studied separately for active, reactive and complex power.

4.7.1 Variation of series-capacitor compensation

The amount of series compensation depends on the amount of load and the transmission distance. A transmission line

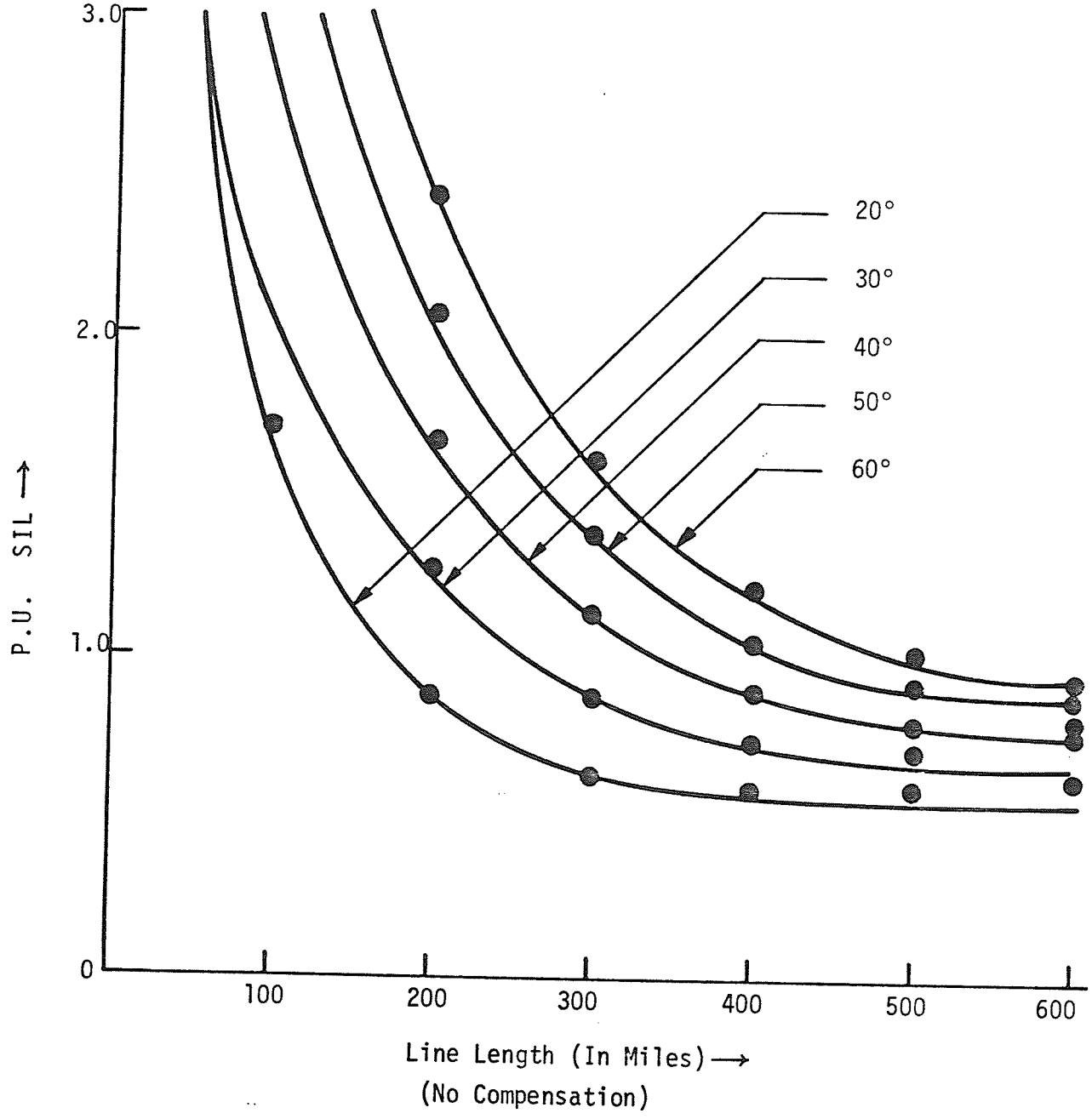


Figure 4.6.1: Effect of Power Angle on Line Loadability.

can be expected to carry more than its designed load due to system growth. It creates the need for addition of more series compensation on the existing lines.

Series compensation varies from 0 percent to 75 percent and two sets of graphs are plotted for active and reactive power components in Figures 4.7.1 and 4.7.2, respectively.

To compare the effect of series compensation on the loadability with the base case, a set of curves in Figure 4.7.3 is drawn for the complex power.

4.7.2 Variation of shunt-reactor compensation

Variation in the amount of shunt compensation can always be expected in a transmission line operating under varying load conditions. As a reactive power controller, it is expected to affect the reactive power loadability of the line.

The effect of shunt compensation is studied on active and reactive components of power loadability of the line. The amount of shunt compensation varies from 0 to 75 percent. Two sets of curves are plotted for active and reactive power components in Figures 4.7.4 and 4.7.5, respectively.

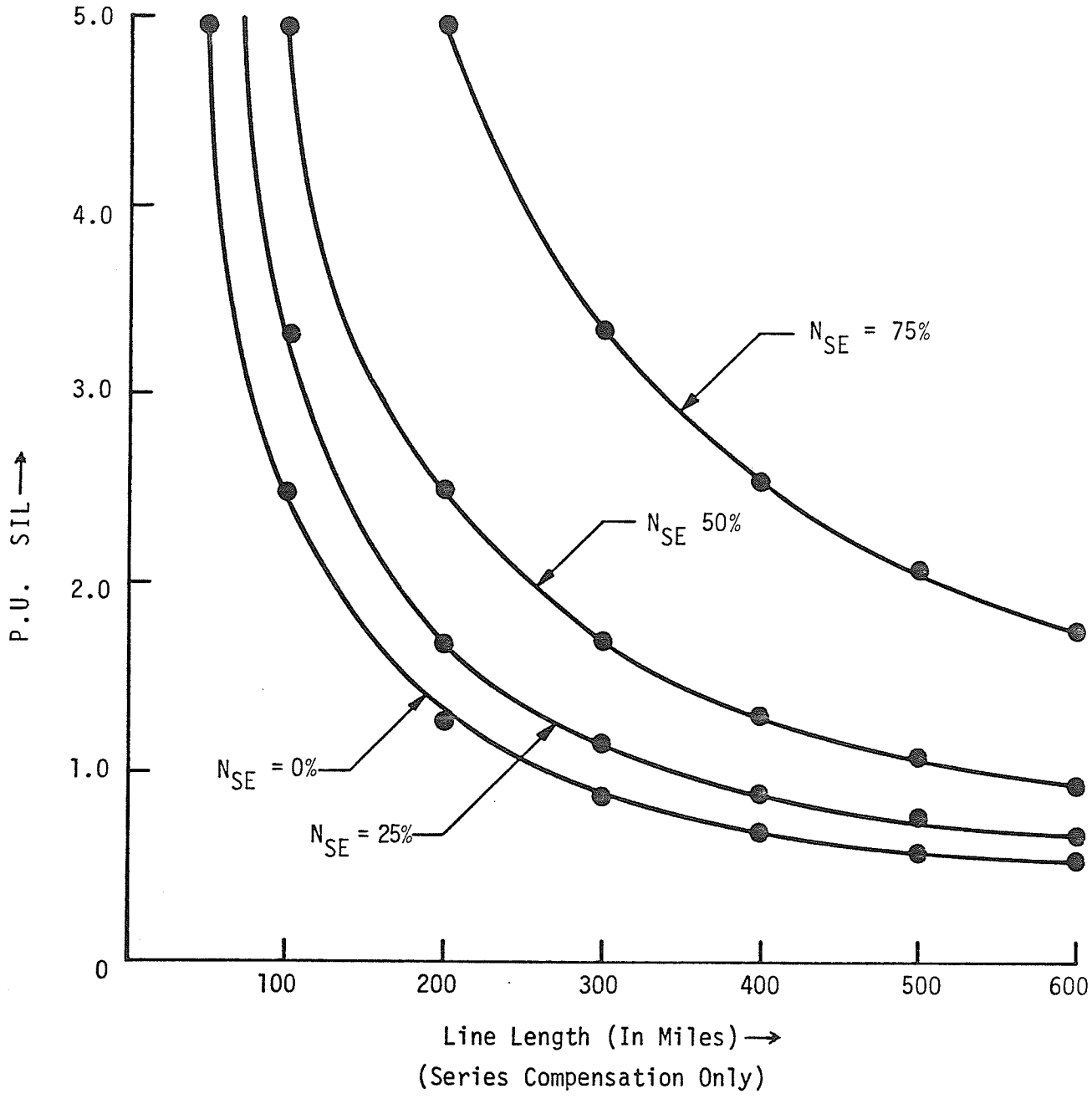


Figure 4.7.1: Effect of Series Compensation on Active Power Component.

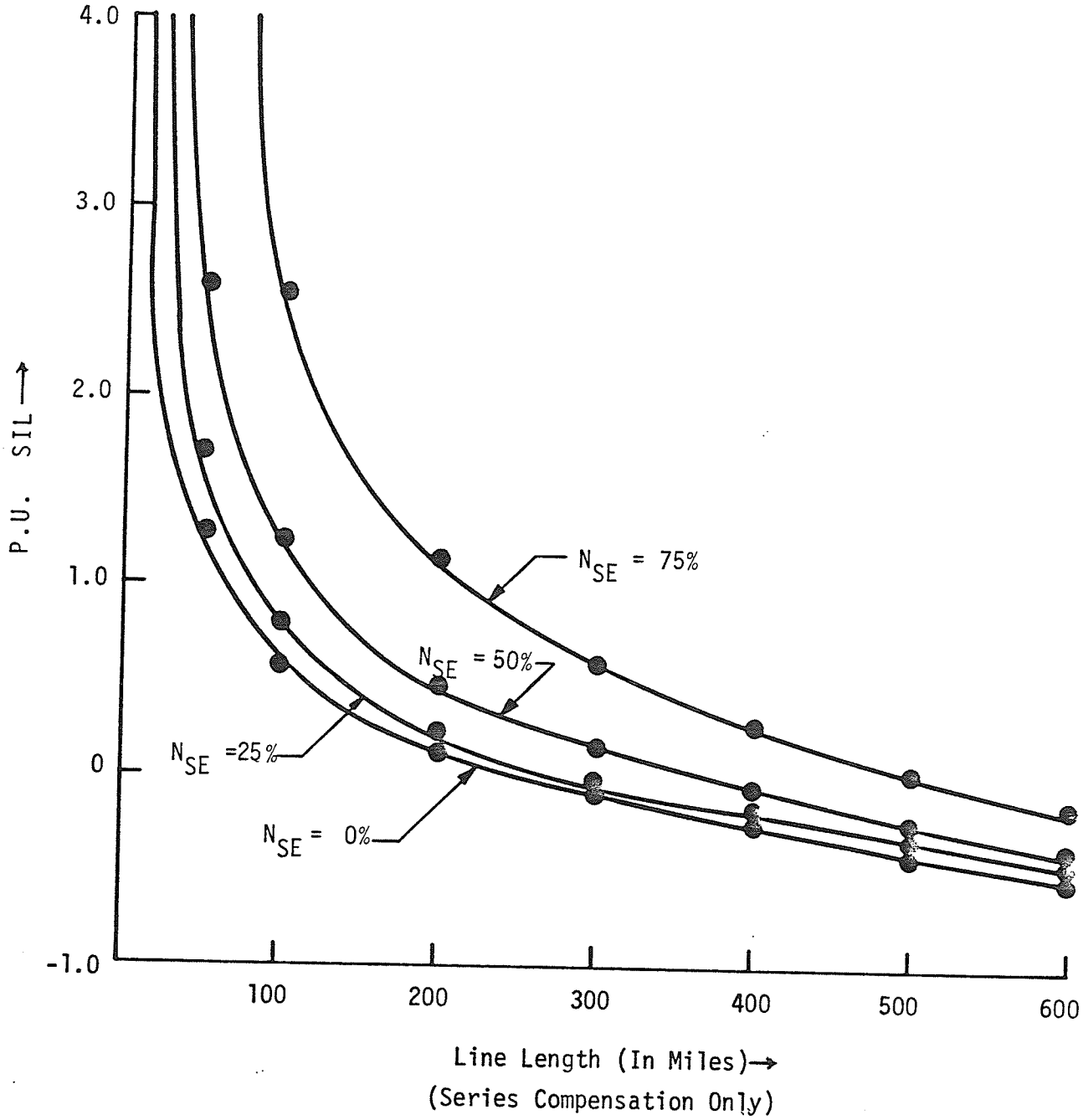


Figure 4.7.2: Effect of Series Compensation on Reactive Power Component.

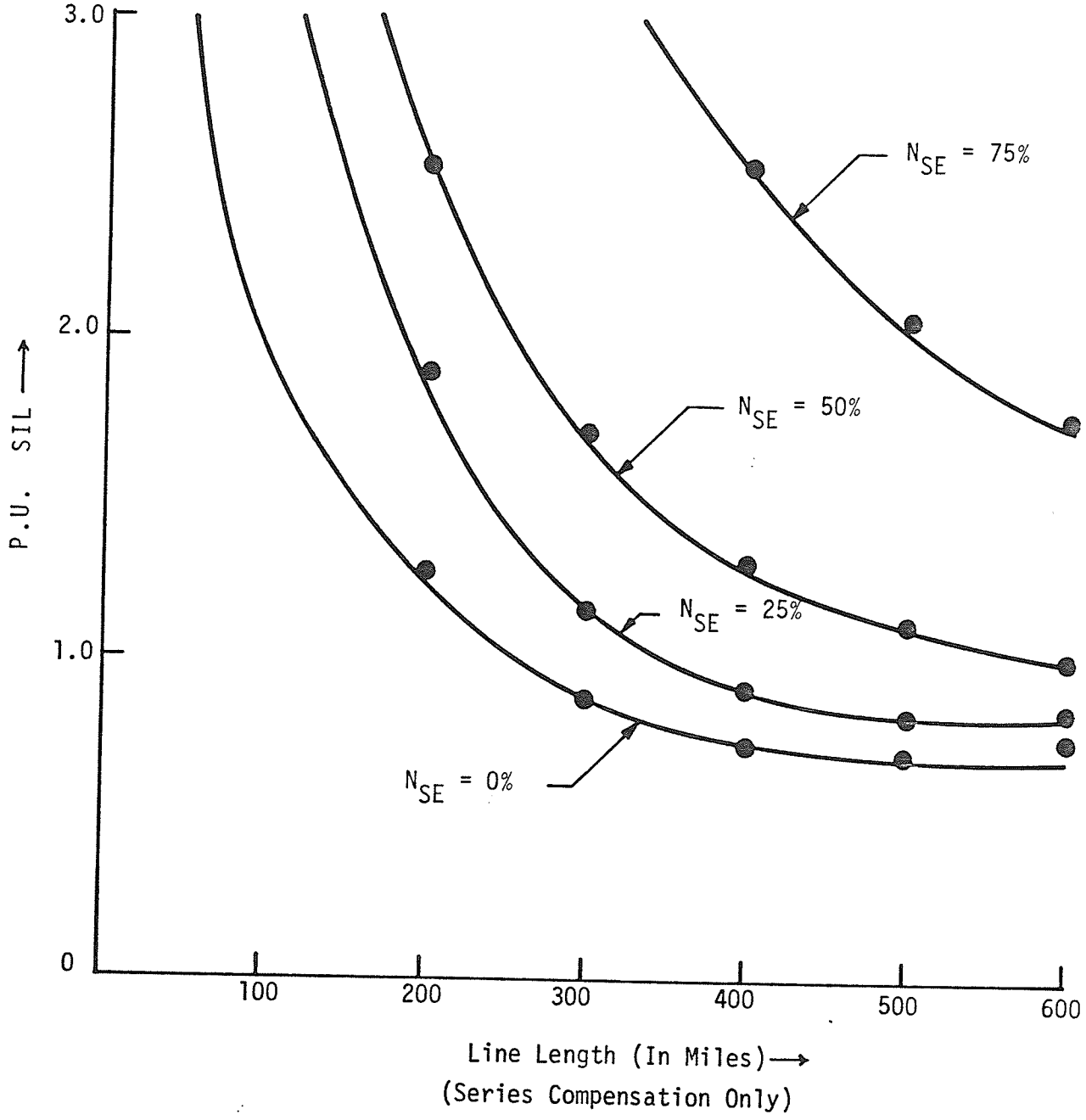


Figure 4.7.3: Effect of Series Compensation on Complex Power Loadability of the Line.

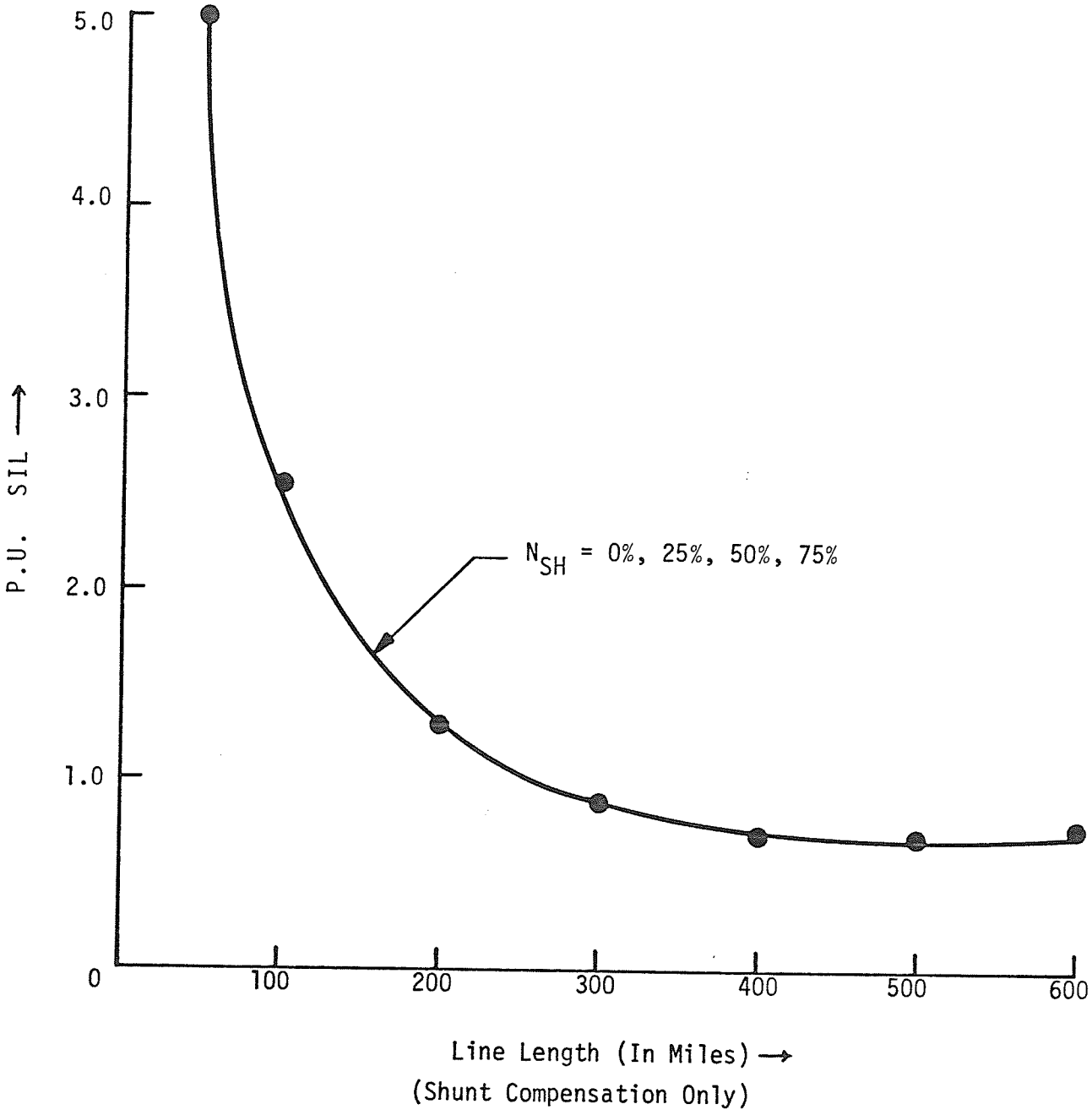


Figure 4.7.4: Effect of Shunt Compensation on Active Power Component.

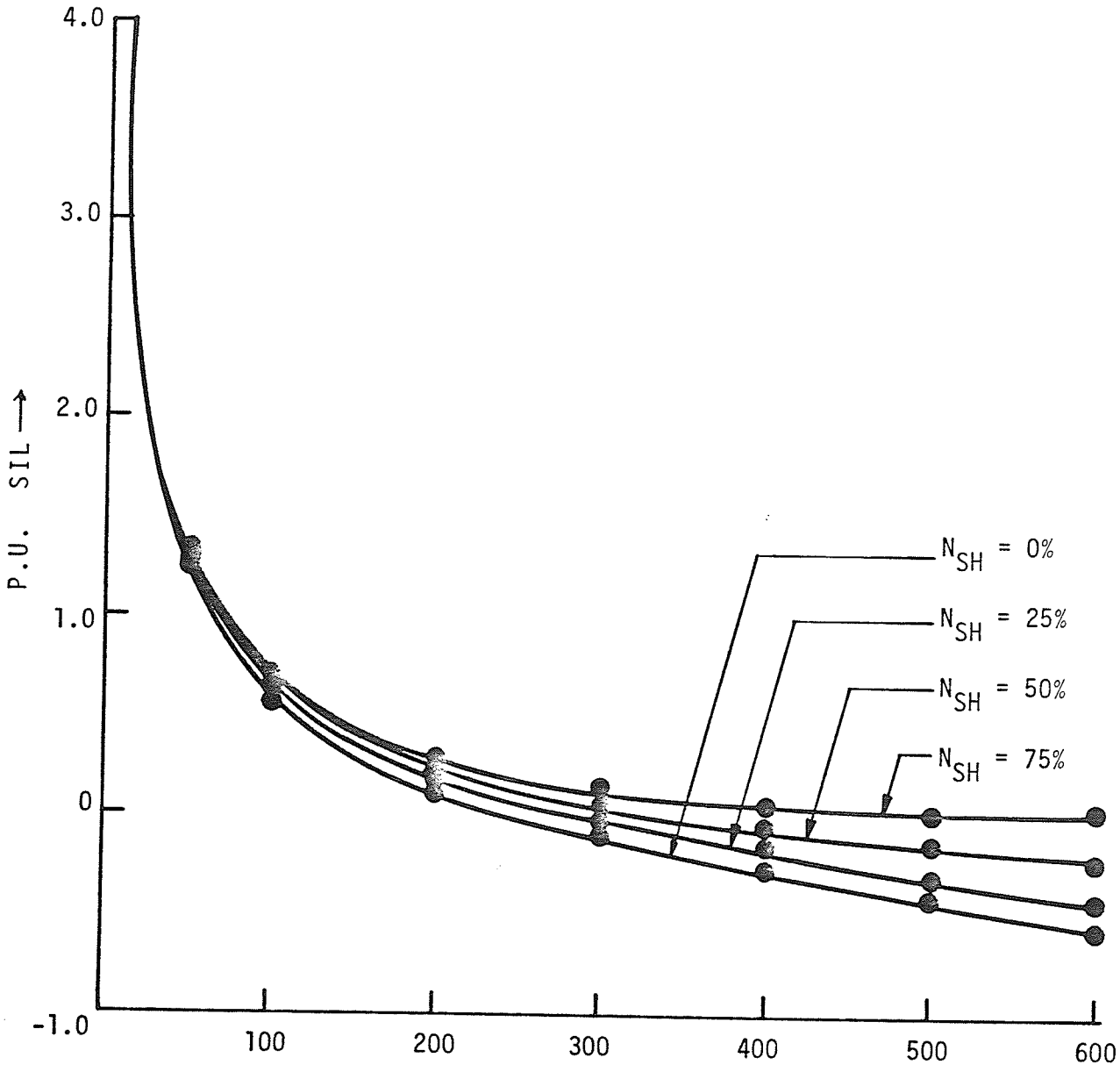


Figure 4.7.5: Effect of Shunt Compensation on Reactive Power Component.

Figure 4.7.6 shows the effect of variation of shunt compensation on the overall loadability of the transmission line.

The extra high voltage lines require both series and shunt compensations. The effect of both series and shunt compensations is studied with different combinations of varying degrees of series and shunt compensations. Series compensation is fixed at 25 percent and the amount of shunt compensation is varied from 0 to 50 percent. The set of curves obtained is shown in Figure 4.7.7a. Figure 4.7.7b shows the curve for 50 percent series and 50 percent shunt compensation. Figure 4.7.7c shows the curve with series and shunt compensations maintained at 75 percent and 70 percent respectively.

4.8 Variation in Line Design Parameters

In the transmission line design, permissible limits of corona losses, radio noise and voltage level of transmission. change the transmission line parameters. Consequently these parameters change the loadability of the transmission line.

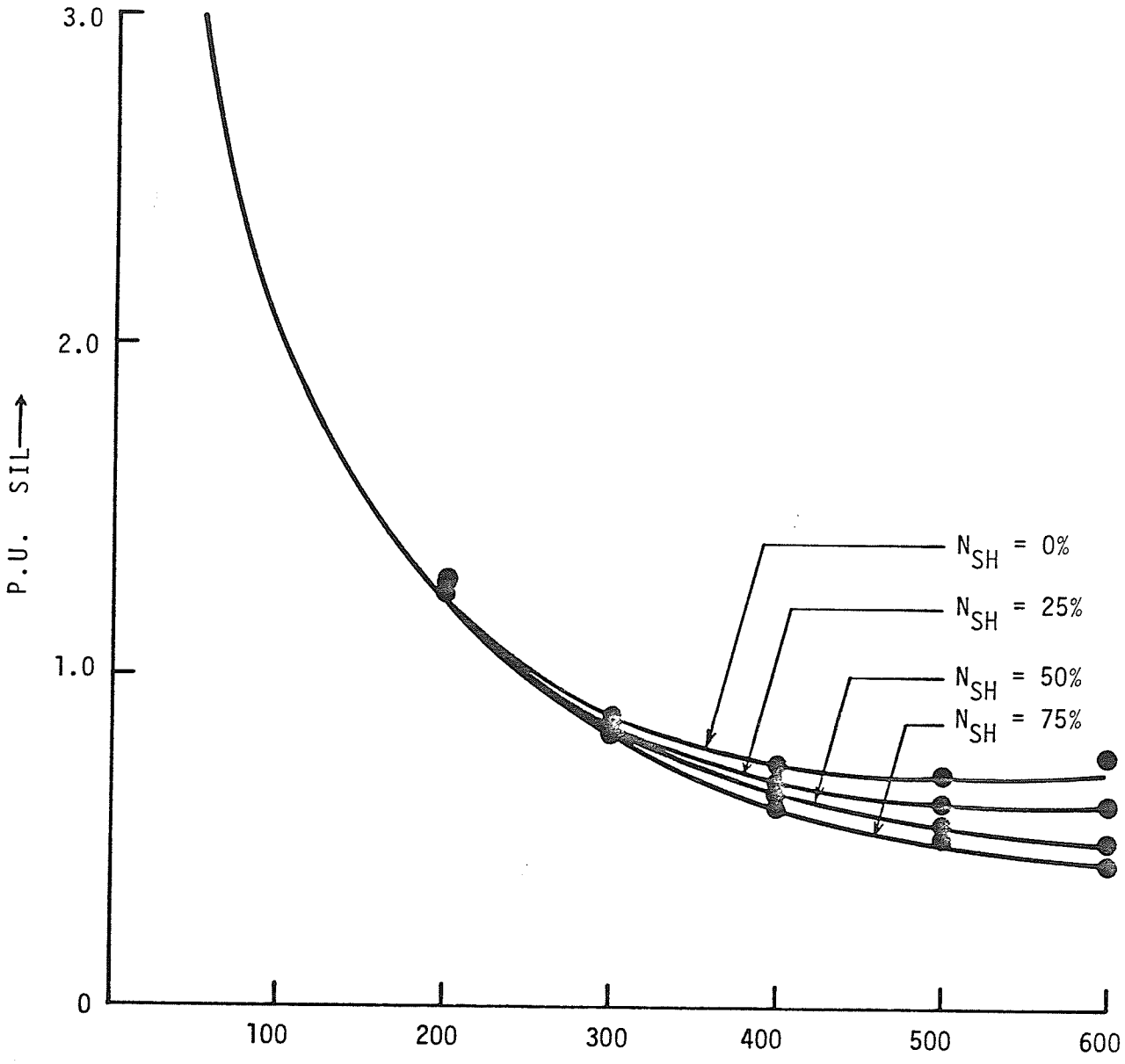


Figure 4.7.6: Effect of Shunt Compensation on Complex Power Loadability of the Lines.

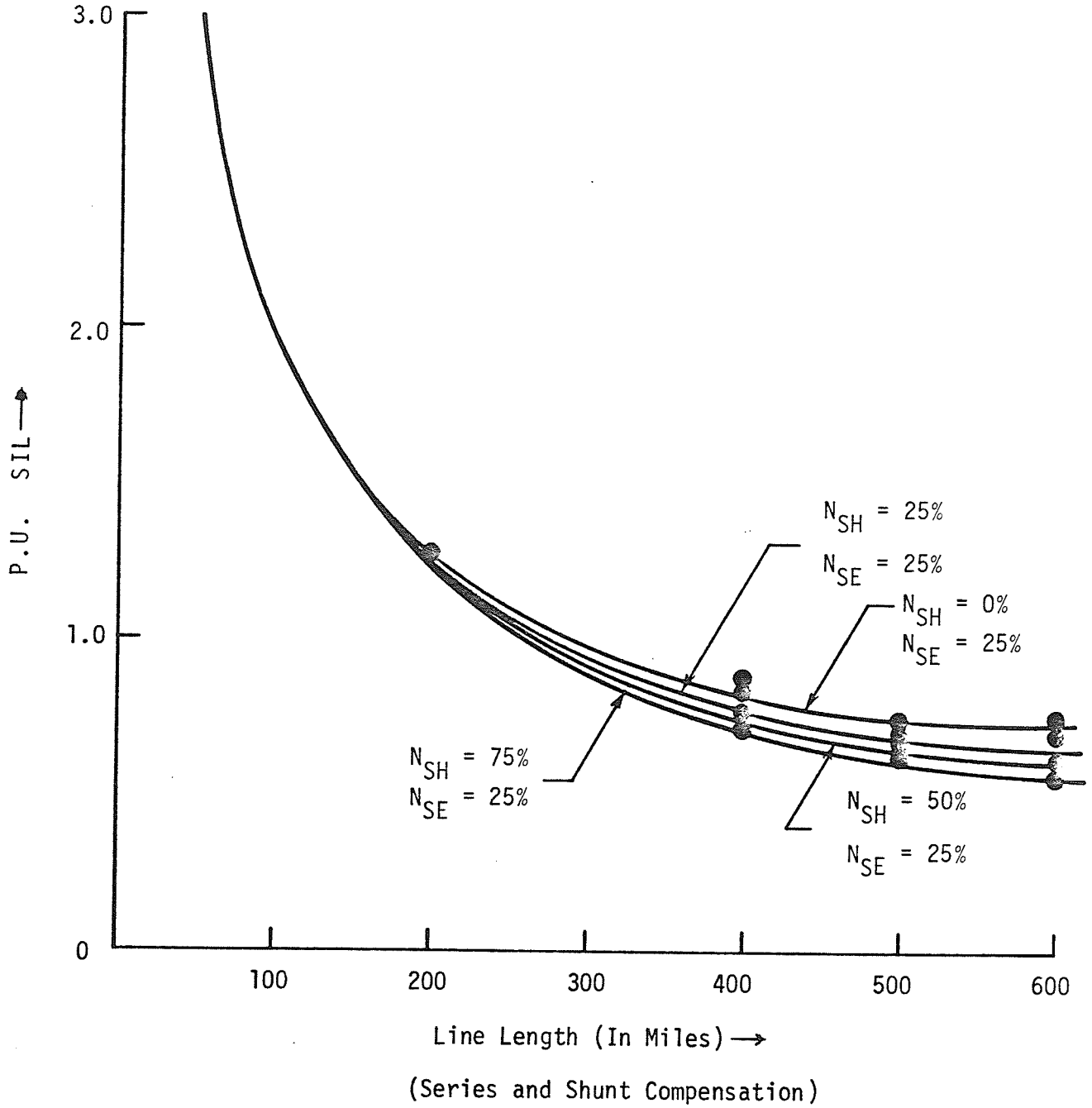


Figure 4.7.7(a):Combined Effect of Series and Shunt Compensations on Complex Power Loadability of the Line.

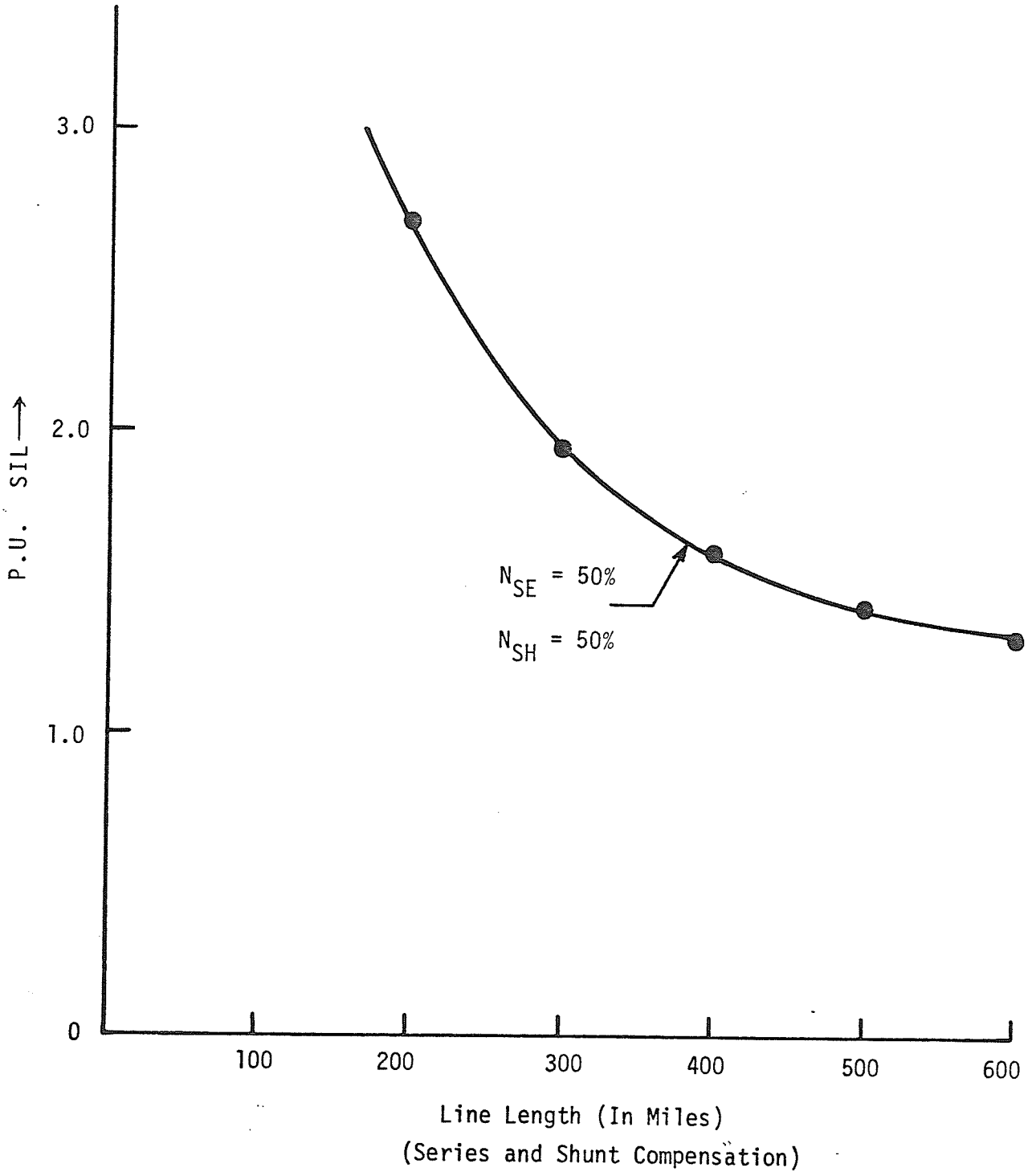


Figure 4.7.7(b): Effect of Series and Shunt Compensation on Line Loadability.

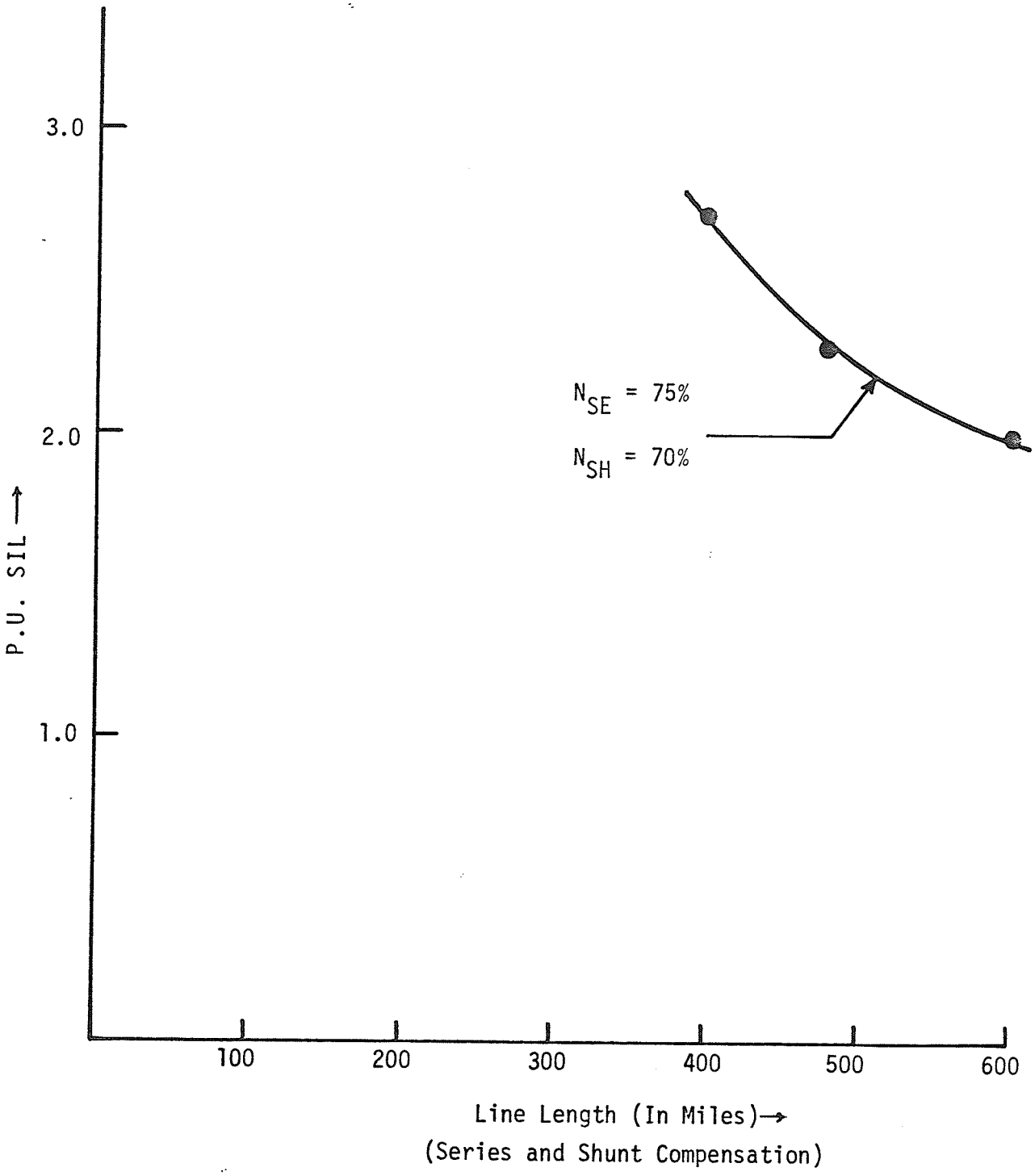


Figure 4.7.7(c): Effect of Series and Shunt Compensation in Line Loadability.

4.8.1 Variation of number of conductors per phase

To study the effect of changing the number of conductors in a bundle three different cases are considered. The number of conductors per phase has been varied from the base case figure of 12 to 14, 16 and 18. The analytical results obtained are plotted along with the base case as shown in Figure 4.8.1.

4.8.2 Variation of intra-bundle spacing

For the reasons stated above, and with an increase in the number of conductors, a change in the intra-bundle spacing is possible.

The spacing has been varied from 14 inches to 16, 18 and 20 inches. The results obtained are plotted in Figure 4.8.2

4.8.3 Variation in phase separation

Figure 4.8.3 shows the different curves obtained with varying the phase separation from 68.5 feet to 88.5 feet in equal steps of 5 feet each.

4.8.4 Variation in conductor size

To observe the effect of conductor size on line loadability, different conductor sizes as shown in Table

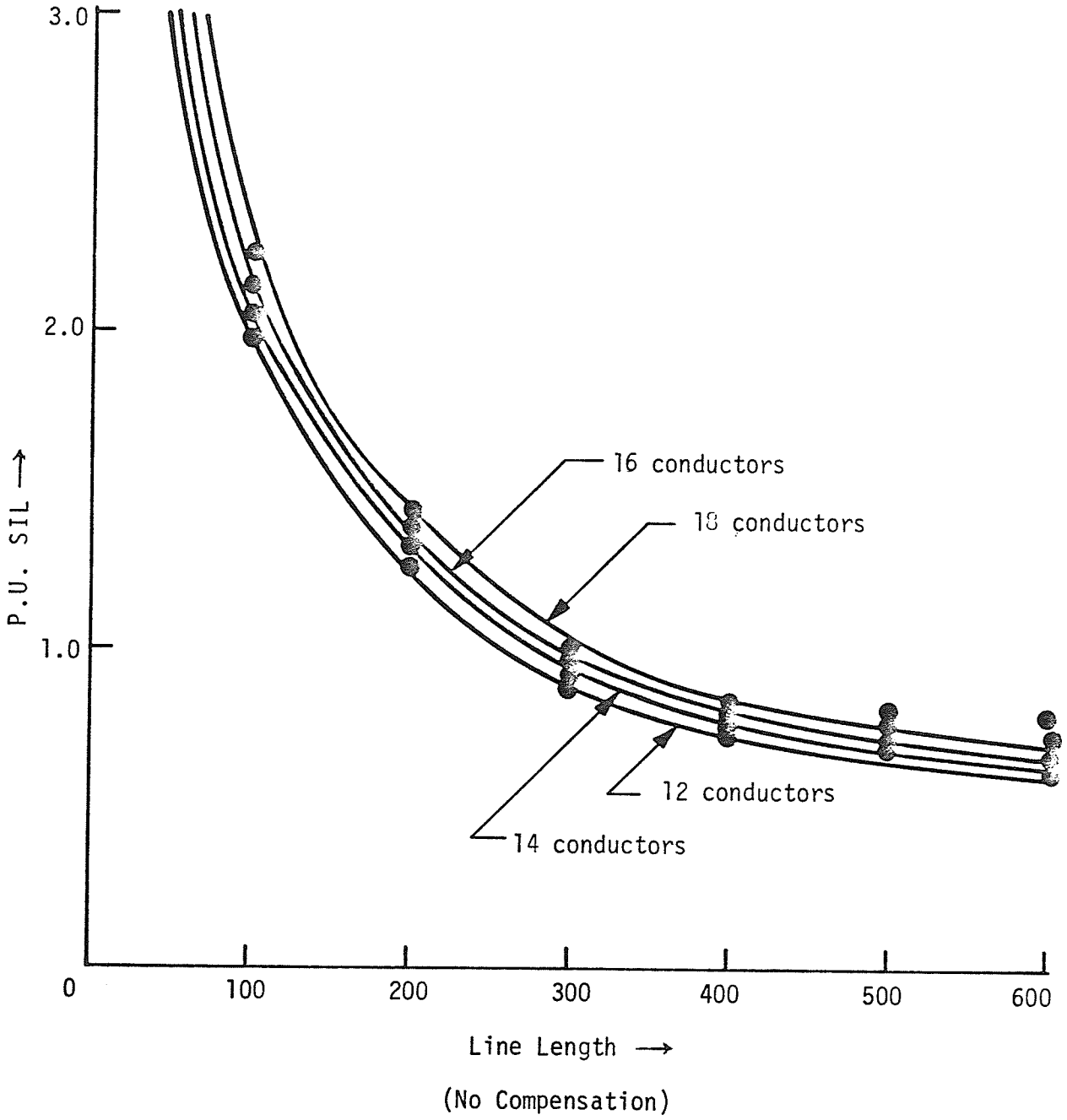


Figure 4.8.1: Effect of Number of Conductors in a Bundle on Line Loadability.

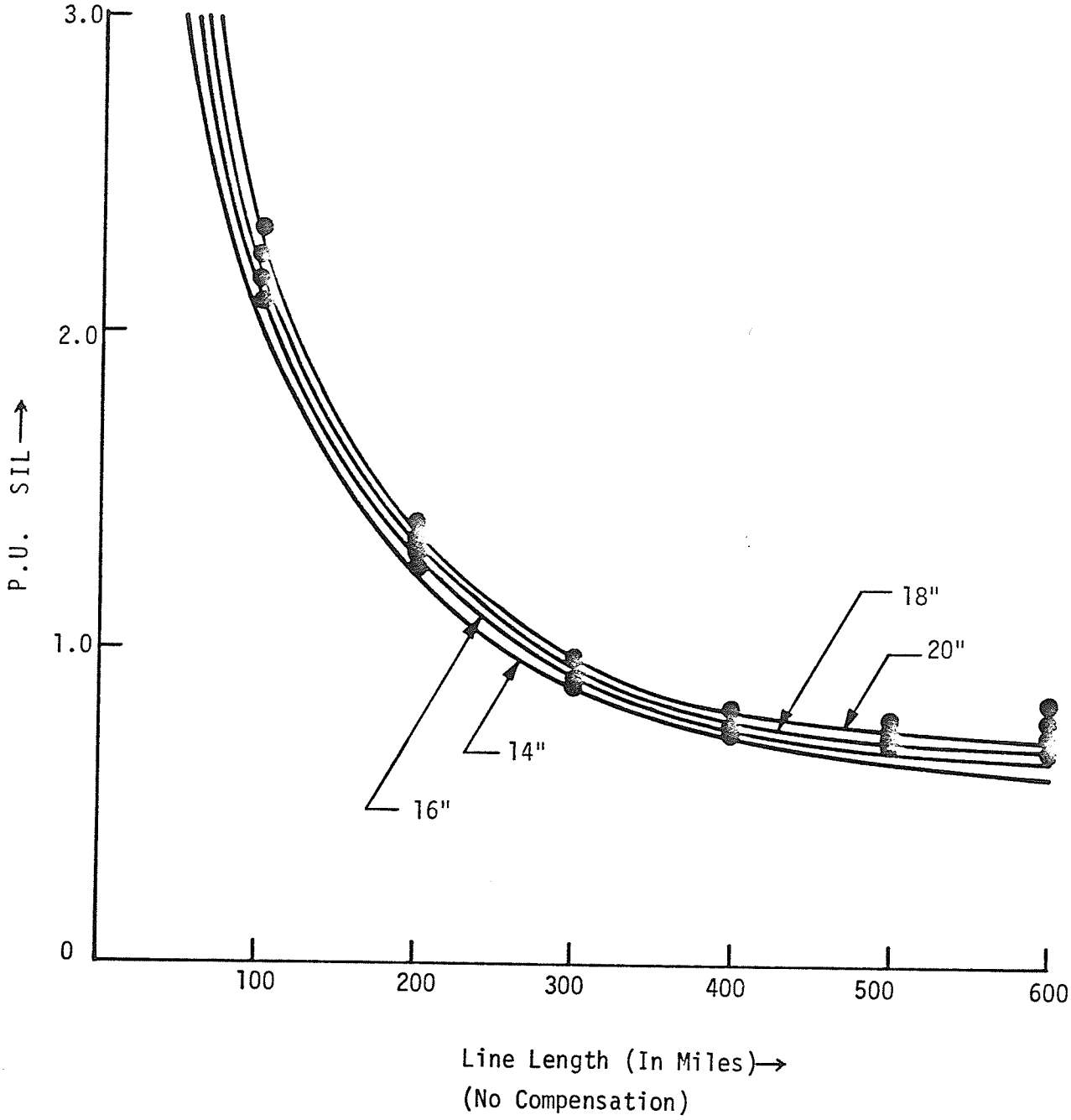


Figure 4.8.2: Effect of Intra-Bundle Spacing on Line Loadability.

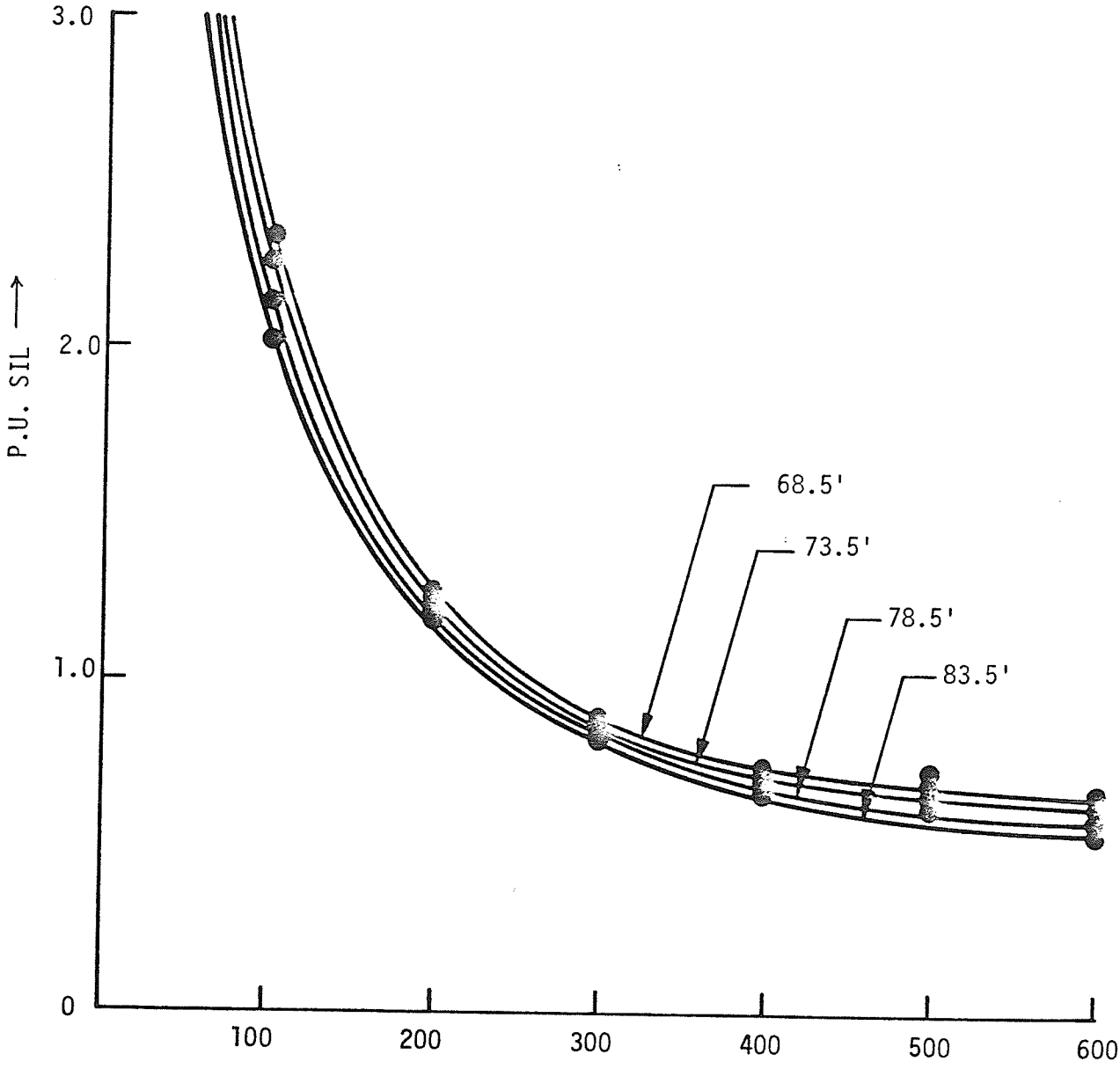


Figure 4.8.3: Effect of Phase Separation on Line Loadability.

4.8.1 has been used in the analysis. The results obtained are plotted in Figure 4.8.4.

TABLE 4.8.1

1781	MCM	ACSR	84/19
2156	MCM	ACSR	84/19
2312	MCM	ACSR	84/19
2515	MCM	ACSR	84/19

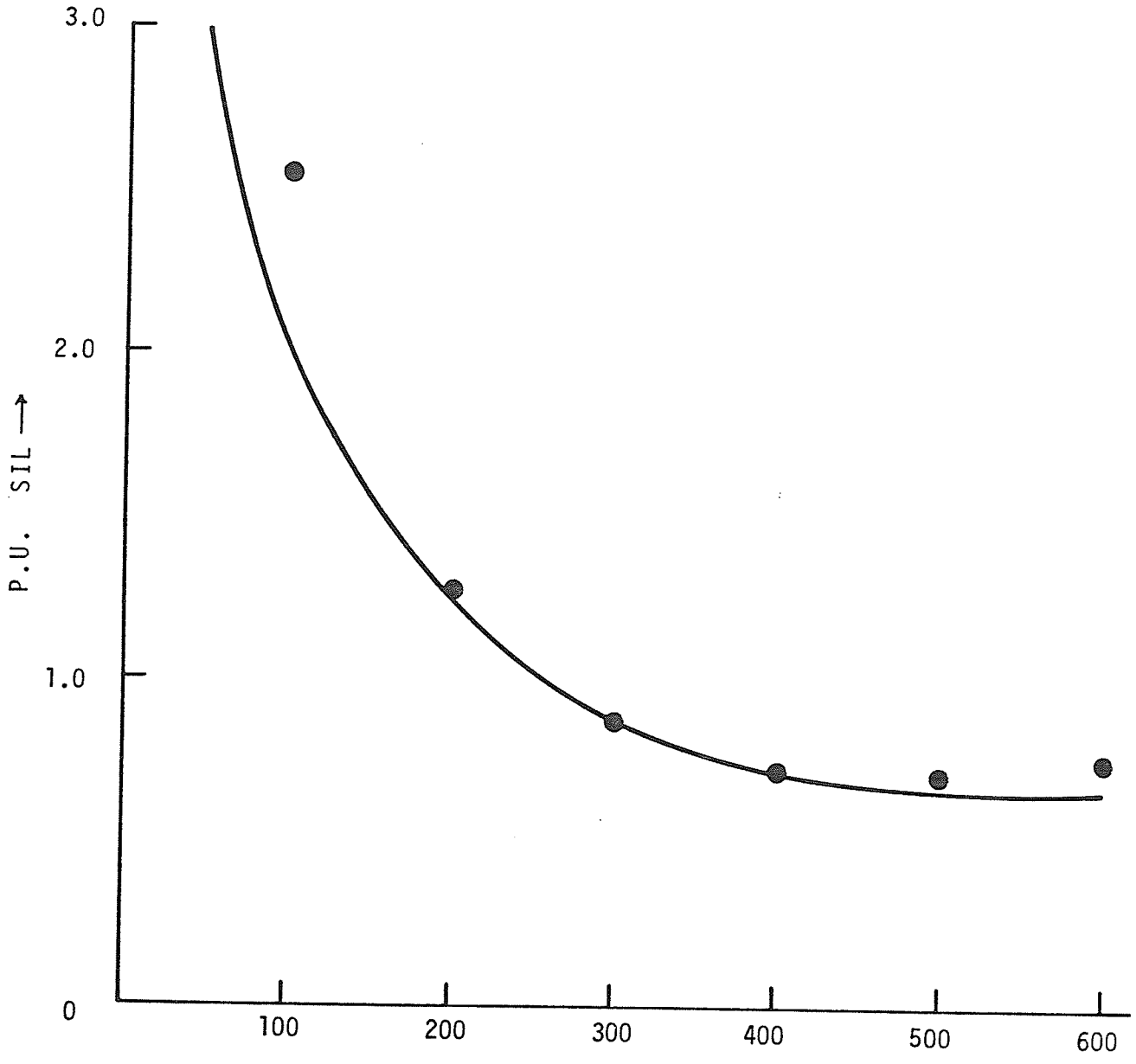


Figure 4.8.4: Effect of Change of Conductor Size on Line Loadability.

CHAPTER FIVE

DISCUSSION OF RESULTS AND CONCLUSIONS

In the previous chapters the effects of various parameters on the transmission line loadability have been studied. The results obtained from these studies have been documented in the form of graphs. In this chapter, these results are analyzed and their significance interpretted. Based on these studies and analysis, conclusions have been drawn.

5.1 Loadability Expressions

It can be seen that the equations for active, reactive and complex power surge impedance loading factors (see equations 4.19, 4.20 and 4.21) for series and shunt compensated lines are generalized. These are applicable to any line operating at any voltage. The expressions are simple and give an idea of the loadability of transmission lines as a function of distance and power angle without the use of a computer. They provide the opportunity for examination of the effects of series-capacitor and shunt-reactor compensations, voltage drop, power angle and transmission line design parameters on the loadability. These relations give better understanding of the principles of transmission

line operation and should help the transmission planning engineers to make reasonable estimates of the line loadability.

5.2 Analytical Loadability Curves

Figure 4.3.1 shows the active, reactive and complex power loadability curves of the line. 1.0 SIL points occur at a line length of approximately 260 miles for the active power loadability curve. It also can be seen from the reactive power curve that the var input to the line is zero at the same line length (260 miles). It shows that the flow of reactive power is in the reverse direction of active power, requiring compensation of the voltage drop (ohmic drop) to zero. The negative (defficient) values of vars shown by the curve beyond 260 miles indicate that to maintain equal voltage at both ends of the line, the sending end must receive vars from the line.

The upward trend in the complex power loadability curve at the ends shows the effect of reactive power components at the sending and receiving ends of the transmission line.

Figure 4.3.2 shows the standard analytical curve derived from the constant and variable power angle curves. The constant power angle curve xyz gives very high loadability

values for lines 50 to 170 miles long. The loading of lines at these values is not possible due to their thermal limitations. However, for short-distance bundled conductor lines, loadability at 4.0 P.U. SIL is possible as the current is shared by different conductors in the bundle and hence thermal limitation is not a problem. The curve satisfies the stability and thermal limitations for the transmission lines from 170 miles to 600 miles in length. The variable power angle curve x'yz' satisfies the thermal and stability limitations for 50 to 170 mile long lines. For line lengths between 170 to 600 miles, it shows that the stability limitations are not satisfied and the increase in loadability is achieved at the cost of steady-state-stability margin.

The curve x'z obtained by joining the constant and variable power angle curves as shown in Figure 4.3.2 satisfies the thermal and stability limitations.

5.3 Comparison of Original Standard and Standard Analytical Loadability Curves

Figure 5.3.1 shows the difference between the analytical and the original standard loadability curves. For line lengths of 140 to about 600 miles, the analytical curve gives lower loadability values than the original loadability curve. It can be seen that the analytical curve gives a 1.0 SIL point at 260 miles and not at 300 miles, a generally accepted value as given by the original standard loadability curve. With an increased power angle of 35 degrees (and not 30 degrees

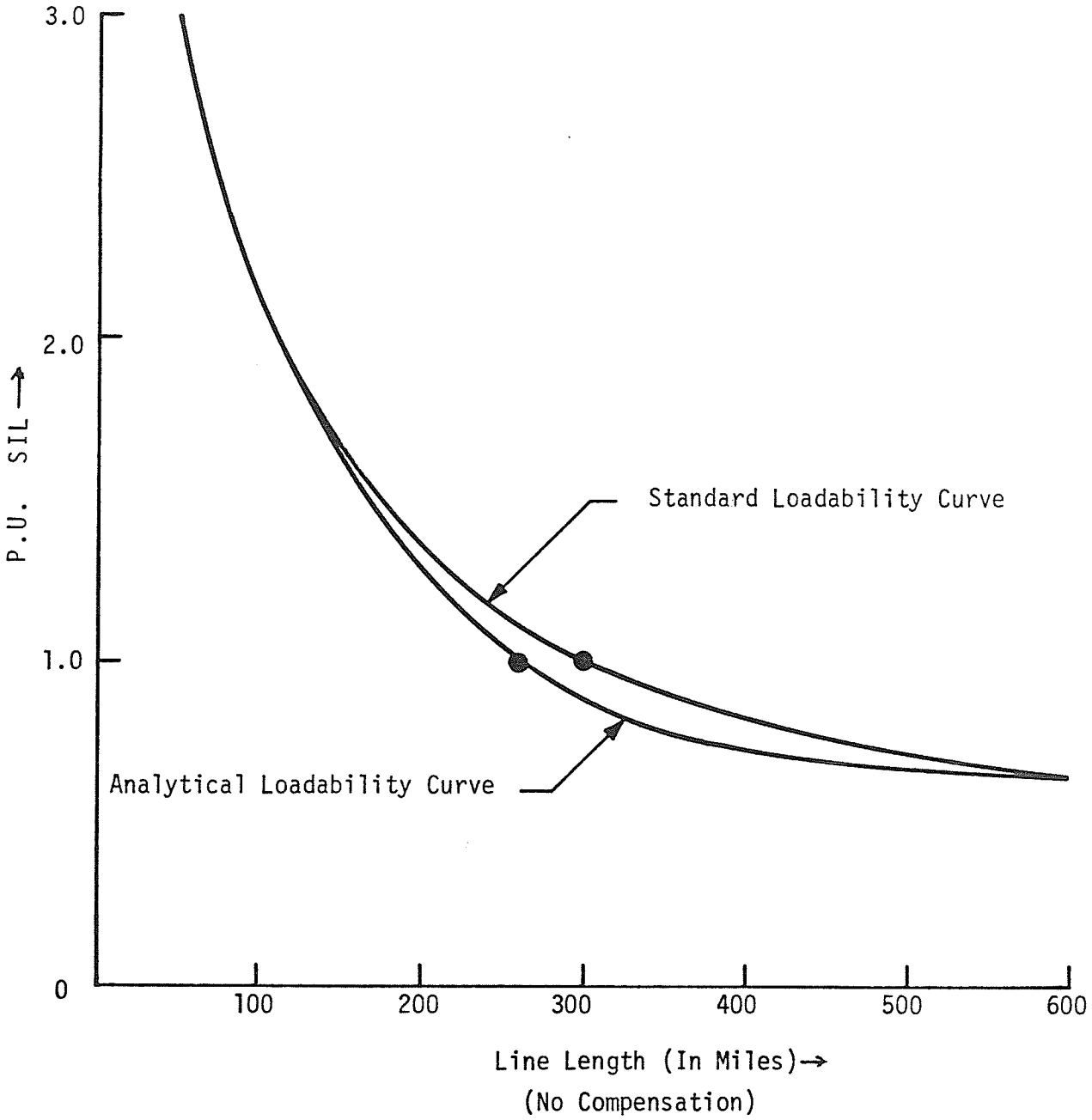


Figure 5.3.1: Comparison of Analytical and Original Standard Loadability Curves.

as generally accepted) the analytical curve gives a 1.0 SIL point at 300 miles. It shows that the analytical curve represents a more conservative evaluation of the loadability than the standard curve.

5.4 Influence of Voltage Increase at Sending End

The voltage increase at the sending end affects the voltage ratio between the two ends. It can be seen from the curves in Figure 4.5.1 that the loadability of the line increases with an increase in voltage at the receiving end. The curves show that the effect of voltage increase is more significant beyond the 170 mile point. The increase in loadability with voltage increase of 3 percent and 5 percent is 0.9 percent (90 MW) and 1.8 percent (180 MW) respectively, for 600 mile long lines.

It shows that the voltage can be increased at the sending end within permissible limits (i.e., up to 10 percent from $\pm$5 percent permissible variation range) and the increased loadability can be used to meet the sudden peaks of load larger than the normal peak loads. The operation of transmission lines under such conditions is possible for very short periods as sustained conditions will affect the transmission line efficiency.

5.5 Influence of Power Angle

Figure 4.6.1 shows the influence of a change in power angle on the line loadability and hence the steady-state-stability margin. The curve for a power angle of 20 degrees shows that the operation of transmission lines approximately 170 miles in length is safe from stability and thermal limitations point of view. Transfer of more power is possible on these lines by increasing the power angle to 30 degrees without the risk of loosing the stability of the power system. The operation of lines at a 20 degree power angle severely reduces the loadability of lines longer than 170 miles.

The loadability curve with a power angle equal to 30 degrees has a 1.0 SIL at 260 miles length. The transfer of more power on the lines of this length is possible at the cost of loosing the stability.

It can also be seen that the increase in loadability with the increase in each degree of power angle is approximately the same, giving an increase of 50 percent in loadability for 60 degrees power angle. It shows the linear relationship between the power angle and the transmission line loadability.

5.6 Influence of Compensation

5.6.1 Influence of series-capacitor compensation

Figure 4.7.1 shows the effect of series compensation on the active power component of transmission lines. The set of curves shows that the loadability increases substantially as the compensation increases. A 1.0 SIL point occurs at 340 miles with 25 percent and at approximately 540 miles with 50 percent series compensation. For 75 percent series compensation curve a 1.0 SIL point occurs beyond 600 miles. It shows that the operation of extra long distance transmission lines at a 1.0 SIL is possible with increased series compensation.

Figure 4.7.2 shows the effect of series capacitor compensation on the reactive power flow on the line. The distance of the zero var point increases with the increase of the series compensation. It occurs at 500 miles with 50 percent series compensation, an increase of 240 miles from when the line is not compensated. It shows that series compensation supplies a portion of the reactive power requirements of the line required to maintain equal voltages at both ends of the line. The amount of shunt compensation required is reduced considerably with the application of series capacitor compensation. It can also be seen that the effect of series

compensation on the reactive power flow reduces as the line length increases. It indicates the increased reactive power demand for compensation due to the increased ohmic voltage drop as the line length increases.

The complex power loadability curves for the series compensated lines are shown in Figure 4.7.3. With 50 percent series compensation the unity surge impedance loading point occurs at 600 miles for complex power instead of 540 miles as for active power loadability curves. It shows that the reactive power supplied by series capacitors increases the utilization of the active power loadability of the line.

It can also be seen that there is a greater improvement in loadability with every additional percent of series compensation. Thus making extra long distance transmission economical and suitable for stable operation.

5.6.2 Influence on shunt-reactor compensation

Figure 4.7.4 shows that there is no effect of shunt compensation on the active power component of the transmission line loadability. The effect on the reactive power component can be seen in Figure 4.7.5 and is clearer for lines longer than 200 miles. It shows the need of shunt compensation for lines longer than approximately 200 miles.

It can also be seen that the distance of the zero var point increases with an increase in the shunt-reactor compensation. It shows the capability of the shunt compensation to meet the reactive power needs of the system with the increase in the transmission distance.

Figure 4.7.6 shows that when the transmission line is shunt compensated only, the complex power loadability is impaired. The 1.0 SIL point occurs at 240 miles with 75 percent compensation instead of 260 miles with 0 percent shunt compensation. This makes clear that when the amount of shunt compensation is more than required to balance the reactive power needs of the line, instead of improvement of the active power component utilization the loadability is hindered by it.

An approximate level for the extent to which a transmission line requires shunt and series compensation can be obtained from the set of curves as shown in Figure 4.7.7 (a, b and c). It can be seen from Figure 4.7.7(a) that with the amount of shunt compensation higher and/or equal to the series compensation, the loadability is reduced as compared to that when it is less than series compensation.

From the discussion in the preceeding sections, it is clear that the series capacitor compensation has the advantageous self-adjusting feature of adjusting the generation

of reactive var supply required with the increase in load. It thus enables a larger load to be transmitted without requiring the increased reactive demand to be supplied by the shunt reactor compensation.

5.7 Variation of Line Design Parameters

5.7.1 Influence of number of conductors per-phase

The increase in the number of conductors of a bundle reduces the inductive and capacitive reactances of the transmission line. The effect of this reduction on the line loadability is shown in Figure 4.8.1. The curves show an increase of 5 percent, 9.5 percent and 13 percent in the line loadability with the increase in the number of conductors in the bundle from 260 to 300 miles with the use of 18 conductors per bundle instead of 12 conductors. The loadability of bundled conductor lines is not limited by the thermal limitations, but heavy loadings for short distance lines will increase I^2R losses.

5.7.2 Effect of intra-bundle spacing

The inductive and capacitive reactances are reduced with the increase in the intra-bundle spacing. This results

in the increase in the loadability of a transmission line. It can be seen from Figure 4.8.2 that the distance at which 1.0 SIL occurs, is increased by 20 miles when the spacing is increased from 12 inches to 20 inches. The percentage increase of 4 percent in the loadability is uniform with each increase in the bundle spacing and the effect of this change is clearly on the long lines. The gain in loadability with larger intra-bundle spacing needs to be economically optimized with the increased costs associated with larger spacings.

5.7.3 Effect of phase separation

The increase in phase separation increases the inductive and capacitive reactances of the line. The percent reduction in loadability is uniform (1.5 percent) for equal steps of 5 feet each, increase in the phase separation. Figure 4.8.3 shows that loadability gained with the use of bundled conductors diminishes to a greater extent with increased phase separation.

5.7.4 Effect of conductor size

The increase in loadability with the increase in conductor size is negligible as shown by Figure 4.8.4. It shows that the choice of conductor size is not related to the loadability of the line.

5.8 Conclusions

1. The expressions developed for calculating the loadability of ac transmission lines are simplified equations as functions of distance and power angle As transmission lines are getting longer and carrying more power, the relationship of distance, power angle, and load is very useful for preliminary design purposes.

2. Using these relationships, it is simple to obtain the loadability curves that are comparable to the original loadability curve. These provide a much wider choice of system parameters, as well as the opportunity to examine the effects of series capacitor and shunt reactor compensations and other parameters.

3. The expressions and the corresponding curves are general in nature. When multiplied by the approximate base power, they will generate loadability information directly.

4. The concept of transmission line loadability expressed in per unit surge impedance loading is extendable to EHV/UHV levels. The loadability curves for all voltage levels seem to be identical to the original loadability curve.

5. The voltage increase at the sending end increases the loadability of the line. The reliability of the system can be increased during sudden and momentarily increases in the load by increasing loadability with an increase in sending end voltage within 5 percent.

6. The variation in line loadability appears to be related in a linear fashion to the change in power angle from 20 to 60 degrees, that is, equal steps of power angle increase bring about almost equal-sized increments in the line loadability.

7. Every additional percent of series compensation yields increasingly greater improvement in the transmission line loadability without risking the stability. This fact tempts us to increase the series compensation to achieve greater economy, but diminishing returns due to increased I^2R losses restrict its use up to a certain level.

8. The increased loadability achieved with the installation of series capacitor can be used in the power system expansion of existing transmission lines.

9. Shunt compensation which is generally required for over-voltage control purposes at EHV levels and above, has a decreasing effect on the line loadability when applied in excessive amounts.

10. With an increase in number of conductors, to transmit a certain amount of power, it is possible to reduce the voltage level.

11. Increases in bundled-conductor spacing increases the loadability.

12. Conductor size has negligible effect on the line loadability. The choice of conductor depends upon the current carrying capability, the economical evaluation of I^2R losses and structural requirements of transmission line towers.

13. An increase in phase separation reduces loadability. This increase is required at high voltage levels, and the increase in loadability associated with higher voltage levels and increases in the number of conductors compensates the loadability lost due to separation.

14. The obtained results are useful for the determination of the most important technical choices in the transmission line design. Economic elements, contingency

performance, right-of-way limitations and other constraints may then be applied to achieve the final overall design.

15. The application of fast-control compensating schemes (such as static compensators) will permit the operation of lines at approximately 60 degrees and full thermal capability of the lines could be achieved resulting in an increase of 50 percent in loadability. However, this point would have to be investigated.

16. The economics of increases in loadability with different parameters is a different subject matter and should be studied separately.

17. The increased compensation increases the amount of compensation equipment and makes the system more complex, and the reliability of the system is reduced due to reduced redundancy. Also, the protection of compensation scheme becomes more costly.

18. In order to arrive at an optimum design of an EHV/UHV transmission line, the technical aspects, economic and reliability evaluations need a careful study and coordination between themselves.

REFERENCES

1. Edith Clarke and S.B. Crary, "Stability Limitations of Long-Distance A.C. Transmission Systems", AIEE Transactions, Vol. 60, 1941, pp. 1051-1059, 1299-1303.

2. H.P. St. Clair, "Practical Concepts in Capability and Performance of Transmission Lines", AIEE Transactions, Vol. 72, December, 1953, pp. 1152-1157.

3. A.F. Gabrielle, P.P. Marchenko and G.S. Vassell, "Electrical Constants and Relative Capabilities of Bundled-Conductor Transmission Lines", IEEE Transactions on Power Apparatus and Systems, Vol. 83, Janaury 1964, pp. 78-92.

4. R.A. Hore, "Advanced Studies in Electrical Power System Design", London: Chapman & Hall, 1966, pp. 227-232.

5. Federal Power Commission, "National Power Survey Part II", U.S. Government Printing Office, 1964, pp. 45-47, 144-145.

6. Federal Power Commission, "National Power Survey Part IV", U.S. Government Printing Office, 1970, pp. IV-2-9, through 17.

7. Edison Electric Institute, "EHV Transmission Line Reference Book", 1972, p. 6.

8. Electric Power Research Institute, "Transmission Line Reference Book, 345 KV and Above", Palo Alto, EPRI, 1975, p. 24.

9. Hugh Hildreth Skilling, "Electric Transmission Lines Text Book", 1951, p. 7.

10. S.B. Crary, "Transmission-Line Electric Loadings", AIEE Transactions, Vol. 63, 1944, pp. 1198-1204.

11. R.D. Dunlop, R. Gutman & P.P. Marchenko, "Analytical Development of Loadability Characteristic for EHV and UHV Transmission Lines", IEEE Transactions on Power Apparatus and Systems, Vol. 98, No. 2, March/April 1979, pp. 606-617.

12. E.W. DuBois, J.F. Fairman, Jr., D.E. Martin, C.M. Murphy & J.B. Ward, "Extra-Long-Distance-Transmission", AIEE Transactions, February 1962, pp. 1108-1116.

13. S.B. Crary and L.E. Saline, "Comparison of methods for improving the stability of high-voltage transmission systems", CIGRE Report No. 307, 1952.

14. G. Jancke, K.S. Smedsfelt and P. Hjertberg, "380 KV series capacitors in Sweden", CIGRE Report No. 322, 1954.

15. S. Lalander and L. Norlin, "The use of series capacitors on high voltage transmission systems", CIGRE Report No. 330, 1958.

16. E.W. Kimbark, "Improvement of system stability by siwtched series capacitors", IEEE Transactions, Power Apparatus and Systems, Vol. PAS-85, February 1966, pp. 180-188.

17. A.A. Johnson, J.E. Barkle & D.J. Povejsil, "Fundamental Effects of Series Capacitors in High-Voltage Transmission Lines", AIEE Transactions, Vol. 70, 1951, pp. 526-532.

18. Simpson Linke, "Surge-Impedance Loading and Power-Transmission Capability Revisited", IEEE Transactions, Paper No. A77-249-6, PAS-96, No. 4, July/August, 1977, p. 1079, Full text in IEEE Publication 77CH 1190-8 PWR.

19. William D. Stevenson, Jr., "Elements of Power System Analysis", McGraw-Hill Book Company, 1962, pp. 120, 143.

20. Richard K. Moore, "Travelling-wave Engineering", McGraw-Hill Book Company, 1960, pp. 28-30.

21. J.D. Ainsworth, C.B. Cooper, E. Friedlander and H.L. Thanawala, "Long Distance A.C. Transmission Using Static Voltage Stabilizers and Switched Linear Reactors", CIGRE Report No. 31-01, 1974.

22. H.L. Thanawala, W.O. Kelhan and W.P. Williams, "The Application of Static Shunt Reactive Compensators in Conjunction with Line Series Capacitors to Increase the Transmission Capabilities of Long A.C. Lines", CIGRE Report No. 31-09, 1976.

23. L.O. Barthold, H. Becker, J. Dalzell, C.B. Cooper, H.B. Norman, C.A. Peixoto, K. Reichert, J.C. Toy, and B. Thoren, "Static Shunt Devices for Reactive Power Control", CIGRE Report No. 31-08, 1974.

24. Aleksa Cavrilovic, "Reactive Compensation for Electrical Power", Electrical Review, 17 August 1973, pp. 231-233.

25. H. Schweickardt and G. Romegialli, "The Static VAR Source in EHV Transmission Systems and its Control", Brown Boveri Review, Baden, 9-78, pp. 585-589.

26. L. Gyugyi, R.A. Otto & T.H. Putman, "Principles and Applications of Static-Thyristor Controlled Shunt Compensators", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, No. 5, Sept./Oct., 1978.

27. K. Reichert, J. Kanferle and H. Glavitsch, "Controllable Reactor Compensator for More Extensive Utilization of High Voltage Transmission Systems", CIGRE Paper No. 31-04.

28. R. Banks, E. Friedlander and A. Gavrilovic, "Application to EHV Transmission of Static Compensators Using Saturated Reactors", Power Transmission Division of GEC Swtichgear Limited, Stafford, England, pp. 153-154.

29. Belur S. Ashok Kumar, K. Parthasarathy, F.S. Prabhakara, and H.P. Khinch, "Effectiveness of Series Capacitors in Long Distance Transmission Lines", Transactions on Power Apparatus and Systems, Vol. PAS-90, No. 5/6, May/June 1970, pp. 941-951.

30. M.Z. Tarnavecky, "ELD, EHV/UHV Transmission Line Design", Graduate Class Notes for Course No. 24.755.

31. "Series Capacitors increase EHV Capacity", Electrical World, May 1974, pp. 52-54.

32. A.B. Pyle, "Series Capacitors Boost EHV System Capability", Electrical World Review, Dec. 26, 1966, pp. 46-48.

33. Westinghouse Electric Corporation, "Electrical Transmission and Distribution Reference Book", 1964, pp. 280-81, 479.

34. David Holliday and Robert Resnick, "Fundamentals of Physics", New York, John Wiley & Sons, 1970, p. 796.

APPENDIX A

Characteristic impedance of the series and shunt compensated line from equations (4.14) and (4.17) is

$$Z_c''' = \left(\frac{1 - N_{SE}}{1 - N_{SH}} \times \frac{\omega L}{\omega C}\right)^{\frac{1}{2}} = \left(\frac{1 - N_{SE}}{1 - N_{SH}}\right)^{\frac{1}{2}} Z_c \qquad (A.1)$$

The phase constant of the series and shunt compensated line from equations (4.15) and (4.18) is

$$\beta''' = [(1 - N_{SE})(1 - N_{SH}) \quad \omega L \omega c]^{\frac{1}{2}}$$

$$= [(1 - N_{SE})(1 - N_{SH})]^{\frac{1}{2}} \quad \beta \qquad (A.2)$$

The values of characteristic impedance and phase constant of a series and shunt compensated line are substituted into equations (4.7) and (4.8). The power equations for real and reactive power are then given by

$$P_s' = n \frac{V_R^2}{Z_c} \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right)^{\frac{1}{2}} \frac{\sin S_{SR}}{\sin \{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}} \beta \ell} \qquad (A.3)$$

and

$$Q_s' = n \frac{V_R^2}{Z_c} \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right)^{\frac{1}{2}} \left[\frac{n}{\tan \{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\beta\ell} - \frac{\text{Cos } S_{SR}}{\text{Sin } \{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\beta\ell}\right] \quad (A.4)$$

Simplifying (A.4),

$$Q_s' = n \frac{V_R^2}{Z_c} \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right) \left[\frac{n \cos (\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\beta\ell) - \text{Cos}\delta_{SR}}{\sin (\{(1 - N_{SE}(1 - N_{SH})\}^{\frac{1}{2}} \beta\ell)}\right] \quad (A.5)$$

Complex power of a series and shunt compensated line is

$$S_s' = [(P_s')^2 + (Q_s')^2]^{\frac{1}{2}} \quad (A.6)$$

$$S'_s = \frac{n \frac{V_R^2}{Z_c} \left(\frac{1 - N_{SH}}{1 - N_{SE}}\right)^{\frac{1}{2}} \left[1 + n^2\cos^2(\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\beta\ell) - 2n \cos (\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}}\beta\ell) \cos\delta_{SR}\right]^{\frac{1}{2}}}{\sin [\{(1 - N_{SE})(1 - N_{SH})\}^{\frac{1}{2}} \beta\ell]} \quad (A.7)$$