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POWER SYSTEM TRANSIENT TIE-LINE CONTROL

by

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ABSTRACT

Improvement of transient stability of power systems interconnected with a tie-line is a basic objective considered in this thesis. Control of reactive and real power at various positions in the power systems and tie-line leads to two methods considered herein for increasing transient stability.

Several real and reactive power controllers are presented for improving tie-line transient stability. In particular, a variable reactor is proposed as a tie-line shunt controller and compensator for consideration as a possible alternative to series compensated tie-lines.

Studies showing effect of various controllers in power system models are presented. These studies indicate that significant improvement in transient stability may be obtained without constructing additional parallel transmission lines.

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DEFINITION OF TERMS

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

Power system.	An electric power transmission network comprising ac and dc transmission lines, generators, and loads.
Tie-line.	Any interconnecting transmission line between two power systems.
Transfer reactance.	The effective series reactance of a length of transmission line which is adjusted for the effects of line capacitance, shunt and series reactive components, and transmission propagation phenomena.
Stability.	The ability of a power system or interconnected power systems to maintain synchronism.
Tie-line controller.	Any device or equipment associated with a tie-line for the purpose of increasing stability between or within power systems.
Power angle.	Phase angle between ac voltage vectors at each end of an ac transmission line.
Transient stability.	The ability of power systems at each end of an ac tie-line to maintain synchronism through the first power angle swing across the tie-line following a system disturbance.
Dynamic stability.	The ability of power systems at each end of an ac tie-line to maintain synchronism after the first swing of power angle across the tie-line following a system disturbance.

LIST OF SYMBOLS

Units are converted to per unit values when applicable.

ac	Alternating current (amps).
a_1, a_2	Areas associated with equal area criterion.
A_o, B_o C_o, D_o	Transmission line constants.
b	Constant defined on page 7.
dc	Direct current (amps).
D	Damping constant (MW/radian/second).
$\hat{D}$	Peak swing angle across a tie-line (radians).
δ	Instantaneous power angle between Thevenin voltages at each end of tie-line (radians).
δ_c	Power angle across the tie-line at which the static compensator discontinues its saturation characteristic (radians).
Δ	Symbol to indicate incremental value.
E_1, E_2	Thevenin equivalent voltage magnitudes at each end of a tie-line (KV).
EHV	Extra high volts - above 300 KV.
H_1, H_2	Inertia constants of equivalent power systems at each end of a tie-line (MW-sec/MVA).
j	Complex function $\sqrt{-1}$.
K	Efficiency constant for series compensation.
K'	Incremental constant for a tie-line $\Delta P/\Delta\delta$ (MW/radian).
K_f	Constant defined on page 8.
KV	Voltage magnitude in kilovolts.

l	Length of transmission line section (miles).
MW	Real power in megawatts.
MVA	Megavolt-amps.
MVAR	Megavolt-amps reactive power.
θ_1, θ_2	Absolute instantaneous angle of Thevenin ac voltages of equivalent power systems at each end of the tie-line (radians).
$\hat{P}$	Peak power transfer capability of lossless transmission line (MW).
P_o	Steady state power transferred along lossless transmission line (MW).
P, P_L	Instantaneous power transferred along lossless transmission line (MW).
P_d	Damping power (MW).
p.u.	Per unit.
q	Constant defined on page 11 (MVA).
S	Laplace operator.
γ	Performance index defined on page 79.
t_o, t_1	Duration of temporary power system fault (seconds).
V_B	Voltage magnitude at terminals of shunt controller (KV).
ω	Power system ac frequency (radians/second).
X_C	Capacitive reactance (ohms).
X_L	Total effective transfer reactance of the transmission line between two power systems (ohms).
X_T	Total series reactance of the transmission line with series and shunt compensating devices included (ohms).
Y_l	Transmission line unit admittance (mhos/mile).
Y_L	Transmission line section admittance (mhos).

Y_C, Y_{C2} Instantaneous admittance of shunt controller (mhos).

Y_S Total effective admittance of transmission line and shunt controller at terminal of shunt controller (mhos).

Z_1 Transmission line unit series impedance (ohms/mile).

Z Transmission line section series impedance (ohms).

INTRODUCTION

Electric generating stations were initially installed in close proximity to centres of population and industry so that supply to one city or town was independent from adjacent electric power systems.

Increased demand for electricity at reasonable rates forced system interconnections through transmission lines in order to rationalize electric loads and generators. Firstly, it is often cheapest to construct generating stations at energy sources and transmit the electricity through transmission lines to the centres of demand. Secondly, a reduction of total installed generating capacity is possible when small power systems are integrated into larger systems, hence minimizing capital costs but still maintaining or improving reliability of supply. A third reason for expanding power systems is that large capacity equipment can be used to take advantage of the cheaper rate of power generation.

Today in the 1970's, power systems have expanded to many gigawatts of generation, but still the basic economic advantages of continued interconnection exist. Extra high voltage transmission lines are being constructed to interconnect adjacent power systems.

When transient disturbances or faults tend to drive interconnected power systems out of synchronism and into instability, large surges of current can flow through the tie-line until protective circuit breakers isolate the two power systems. Separating the power systems allows independent recovery to stability and is the usual way of protection against severe transient faults. If the power flow through tie-lines can be rapidly controlled, particularly during transient power surges, then increased damping of the total power system is possible with an increase in limits of stability.

The purpose and aim of this dissertation is to present several effective means of improving stability between two interconnected power systems without necessarily constructing additional tie-lines.

Reactive power control of a tie-line is to effectively control its transfer impedance by either series or shunt reactive devices. With a constant reactance device the transmission line is said to be compensated. If the reactance device is capable of varying its reactance then the transmission line is said to be controlled. Reactive power controllers and compensation devices will be evaluated and it will be shown that shunt compensation and control is a competitive alternative to series compensation and series capacitor switching. A design procedure for shunt reactive power controllers will be demonstrated. Also a shunt compensation and control device for tie-line control will be presented as a possible means of achieving an economic alternative to series capacitors.

Real power control is to inject real power into the power system to counteract system power swings and power surges to improve stability. The high voltage direct current transmission link as a real power controller will be studied with the emphasis on using its ac damping controls to their maximum capability to improve system damping.

Advantages of rapid power control through tie-lines are:

1. Increased steady state power transfer capability.
2. Delayed construction of tie-lines to be added in parallel to existing transmission lines; that is, providing reliability criteria remain satisfied.
3. Reduced series compensation possible because stability limits increased.
4. Improved combined power system transient stability.
5. Possible improvement of system reliability.
6. Possible elimination of dynamic instability or post-first-swing instability with increased system damping.
7. Tie-line protection relay settings may be relaxed a little to allow larger power swings during transient disturbances.

It is hoped above all other things that this thesis will add understanding of the electric power system to the reader.

CHAPTER 1

ANALYSIS OF TIE-LINE CONTROL

1.0 A mathematical tie-line model.

The essence of tie-line control is to increase combined power system transient stability and damping. To illustrate by a simple mathematical model how tie-line control can be attained, consider a two machine equivalent power system separated by a lossless reactive transmission tie-line as in Figure 1.1. A lossless transmission line is an approximation used in many power system stability studies. For this example the reactive transmission line as shown in Figure 1.1 is sufficient to allow two ways to be demonstrated in which power system stability can be improved.

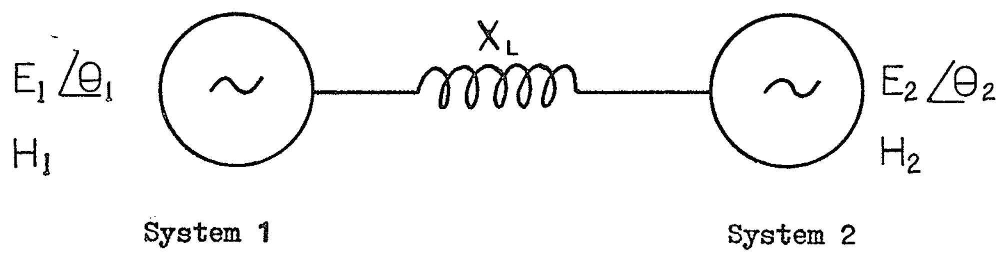


Figure 1.1 Simple power system with tie-line.

Essential quantities and components are in per unit values for convenience and are defined as follows:

X_L = Total effective transfer reactance of the tie-line between System 1 and System 2.

E_1, E_2 = Equivalent voltage magnitudes at each end of tie-line.

θ_1, θ_2 = Equivalent voltage phase angles at each end of tie-line.

H_1, H_2 = Equivalent system inertia constants at each end of tie-line.

δ = $\theta_1 - \theta_2$ and is the relative phase angle between voltages E_1 and E_2.

Two cases of the tie-line control problem are considered. The first case considers a linear solution for δ for different values of line reactance X_L following a perturbation. The second case considers a linear solution for different amounts of damping on System 1 for the same perturbation. The object of these two cases is to show that the maximum excursion of angle δ following a system disturbance is minimized with reduced interconnecting line reactance and/or by increasing system damping. A reduced maximum excursion of δ following a system disturbance indicates improved power system transient stability, a most desirable state.

1.1 Tie-line stability as a function of line reactance X_L.

The power transfer P along the transmission line is defined by the well known equation,

$$P = \frac{E_1 E_2}{X_L} \operatorname{Sin} \delta \qquad (1.1)$$

The linearized equation for incremental power transfer is found from equation 1.1 to be

$$\Delta P = \frac{E_1 E_2}{X_L} \text{Cos } \delta_o \; \Delta\delta, \tag{1.2}$$

where

δ_o = steady state value of δ

$\Delta\delta$ = incremental displacement of δ from δ_o such that

$\delta = \delta_o + \Delta\delta$

ΔP = corresponding incremental power transfer from steady state value P_o such that

$P = P_o + \Delta P$

For fixed values of E_1, E_2, and X_L,

$$\Delta P = K' \Delta\delta \; , \tag{1.3}$$

where

$$K' = \frac{E_1 E_2}{X_L} \text{Cos } \delta_o$$

The angles of the voltages at each end of the tie-line are dependent upon the respective system inertias and the tie-line power flow. If power flow is from System 1 to System 2 (See Figure 1.1) then change in θ_1 due to incremental increase in power ΔP is given by

$$\Delta\theta_1 = \frac{-\omega_o}{2H_1 S^2} \cdot \Delta P \; , \tag{1.4}$$

where $\Delta\theta_1$ = small change in voltage angle θ_1

ω_o = power system ac frequency in radians per second.

S = Laplace operator $j\omega$

H_1 = System 1 inertia constant.

Similarly, change in voltage angle of System 2 due to the same increase in power flow ΔP is

$$\Delta\theta_2 = \frac{\omega_o}{2H_2S^2} \cdot \Delta P \ , \tag{1.5}$$

where $\Delta\theta_2$ = small change in voltage angle θ_2.

Consequently, relative change in power angle δ across the transmission line is defined by

$$\Delta\delta = \Delta\theta_1 - \Delta\theta_2 \tag{1.6}$$

Equations 1.3, 1.4, 1.5, and 1.6 define the dynamic state of the simple linear model of Figure 1.1. These equations are represented by block diagram in Figure 1.2, and can be assimilated into a single second order linear differential equation for case 1 as

$$S^2\Delta\delta + b\Delta\delta = 0 \ , \tag{1.7}$$

where $$b = \frac{K'\omega_o}{2}\left[\frac{1}{H_2} + \frac{1}{H_1}\right]$$

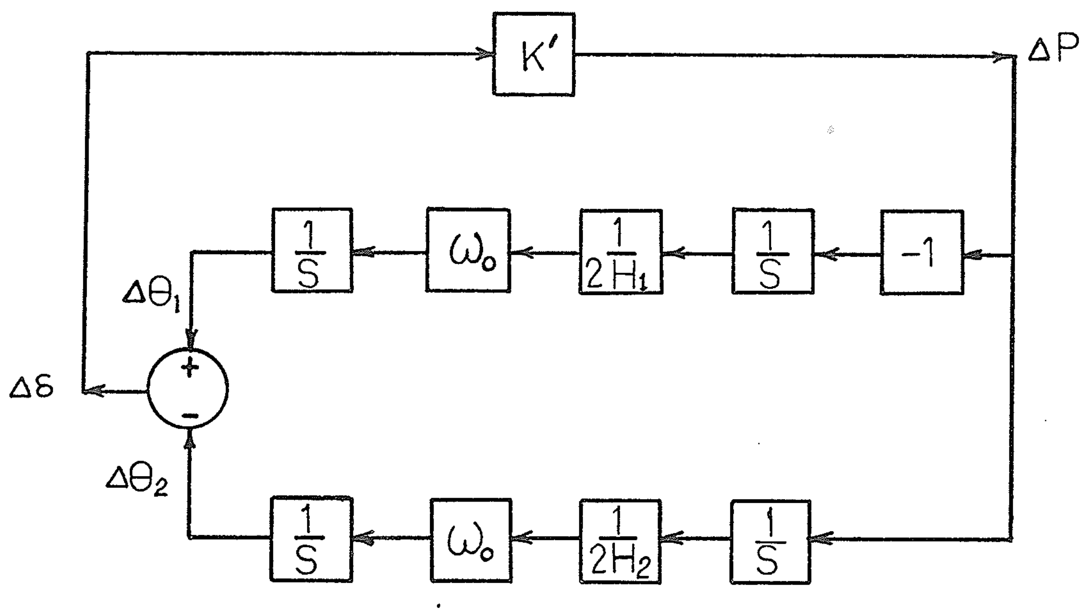


Figure 1.2 Block diagram of undamped linear power system.

To solve the differential equation 1.7, boundary conditions must be defined and will depend upon the initiating disturbance. A suitable solution is obtained when the system is disturbed with a perturbation approaching an impulse function, thus approximating a self-clearing system fault. The solution is:

$$\Delta\delta = \frac{K_f}{\sqrt{b}} \operatorname{Sin} \sqrt{b}\, t \,, \tag{1.8}$$

where $K_f = \left. \frac{d\delta}{dt} \right|_{t\,=\,0}$

and $b = \frac{E_1 E_2}{X_L} \operatorname{Cos} \delta_o \cdot \frac{\omega_o}{2}\left(\frac{1}{H_2} + \frac{1}{H_1}\right)$

$\frac{d\delta}{dt}$ at time zero is a function of the disturbance magnitude, and so, for a particular fault, is considered as a constant K_f. The maximum excursion of $\Delta\delta$ can be determined from the solution and is seen to be directly proportional to $\sqrt{X_L}$ for a given fault.

1.2 Tie-line stability as a function of damping.

Case 2 considers a similar linear solution with damping power added at one end of the tie-line to the power system of Figure 1.1. An expression for the damping power ΔP_d is obtained by assuming arbitrarily that it is directly proportional to System 1 frequency. Such an assumption is analogous to the way amortisseur windings of generators contribute damping power to a power system. If D is a damping constant, then

$$\Delta P_d = D \cdot \Delta\omega_1 \ , \qquad (1.9)$$

where $\Delta\omega_1 = \frac{-1}{2H_1 S} \Delta P$

= change in per unit rotational velocity of vector E_1.

The block diagram for case 2 is essentially the same as case 1, except that the damping power ΔP_d is added as shown in Figure 1.3.

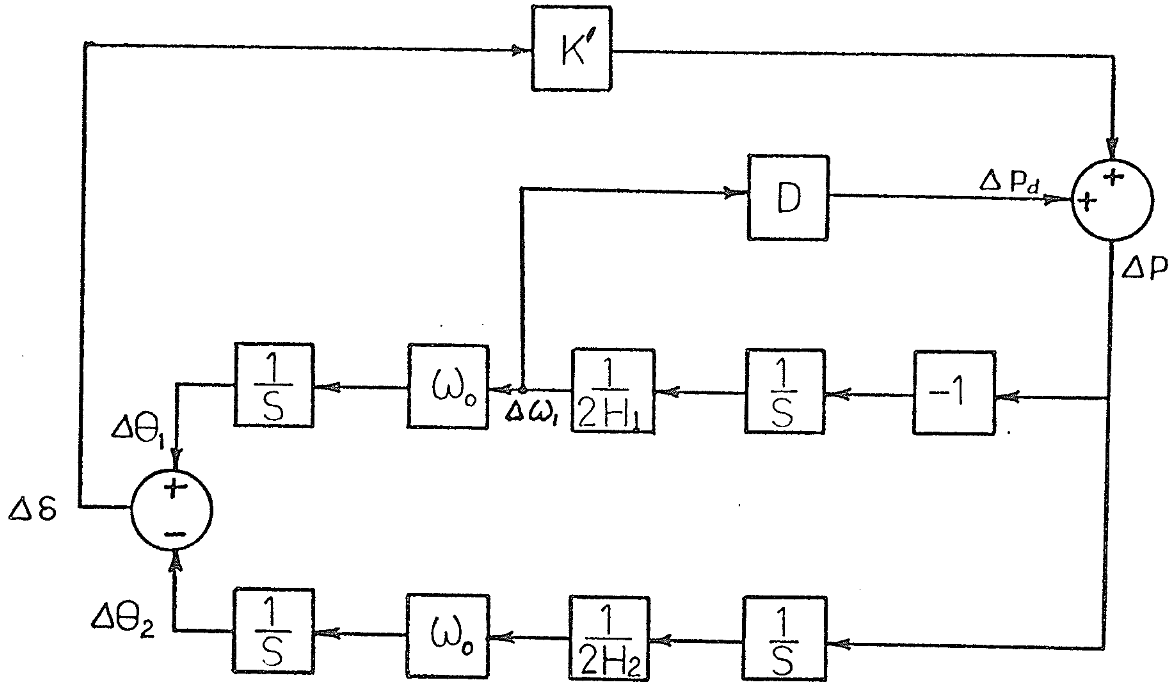


Figure 1.3 Block diagram of linear power system with damping.

The linear second order differential equation derived from the block diagram of Figure 1.3 is

$$S^2\Delta\delta + \frac{SD\Delta\delta}{2H_1} + \frac{K'}{2}\left[\frac{1}{H_1} + \frac{1}{H_2}\right]\Delta\delta = 0 \qquad (1.10)$$

If the system is disturbed similarly to case 1 by a perturbation approaching an impulse function, then the solution is

$$\Delta\delta = \frac{K_f}{q} e^{-\frac{a}{2}t} \text{ Sin } qt , \qquad (1.11)$$

where $K_f = \left.\frac{d\delta}{dt}\right|_{t = 0}$

$$a = \frac{D}{2H_1}$$

$$b = \frac{K\omega_o}{2}\left[\frac{1}{H_1} + \frac{1}{H_2}\right]$$

$$q = \sqrt{b^2 - a^2/4}$$

A solution of the "first swing" is plotted for case 1 and case 2 in Figures 1.4 and 1.5 respectively. These solutions depict the maximum excursion of the power angle $\Delta\delta$ following the same fault disturbance and, hence, indicate the relative transient stability of the faulted system.

Figure 1.4 shows solutions of case 1 for different values of line reactance X_L. It can be seen that the system's transient stability is increased with reduced value of inductive line reactance since peak magnitude of excursion of $\Delta\delta$ reduces with reduced X_L.

Figure 1.5 shows solutions of case 2 for differing values of damping constant D with fixed line reactance $X_L = 0.41$. Transient stability increases with increased damping.

1.3 Two factors affecting transient stability.

The very important conclusions to be emphasized at this point are, firstly, the maximum power angle of the first swing across a transmission line following a disturbance is minimized if the equivalent line impedance is effectively minimized, or the ratio E_1E_2/X_L

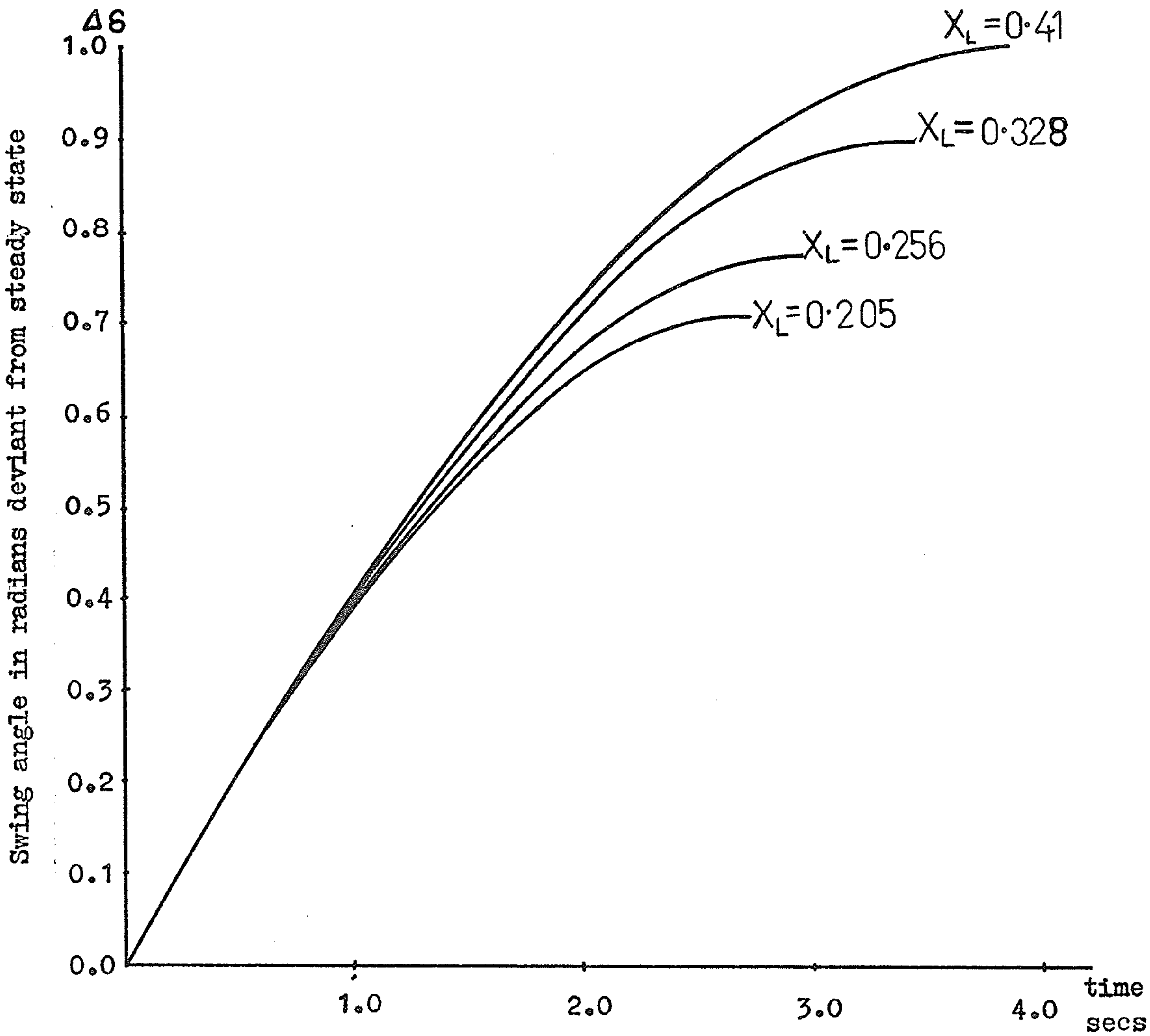


Figure 1.4 Solution to equation 1.7 showing effect of tie-line reactance on system transient stability.

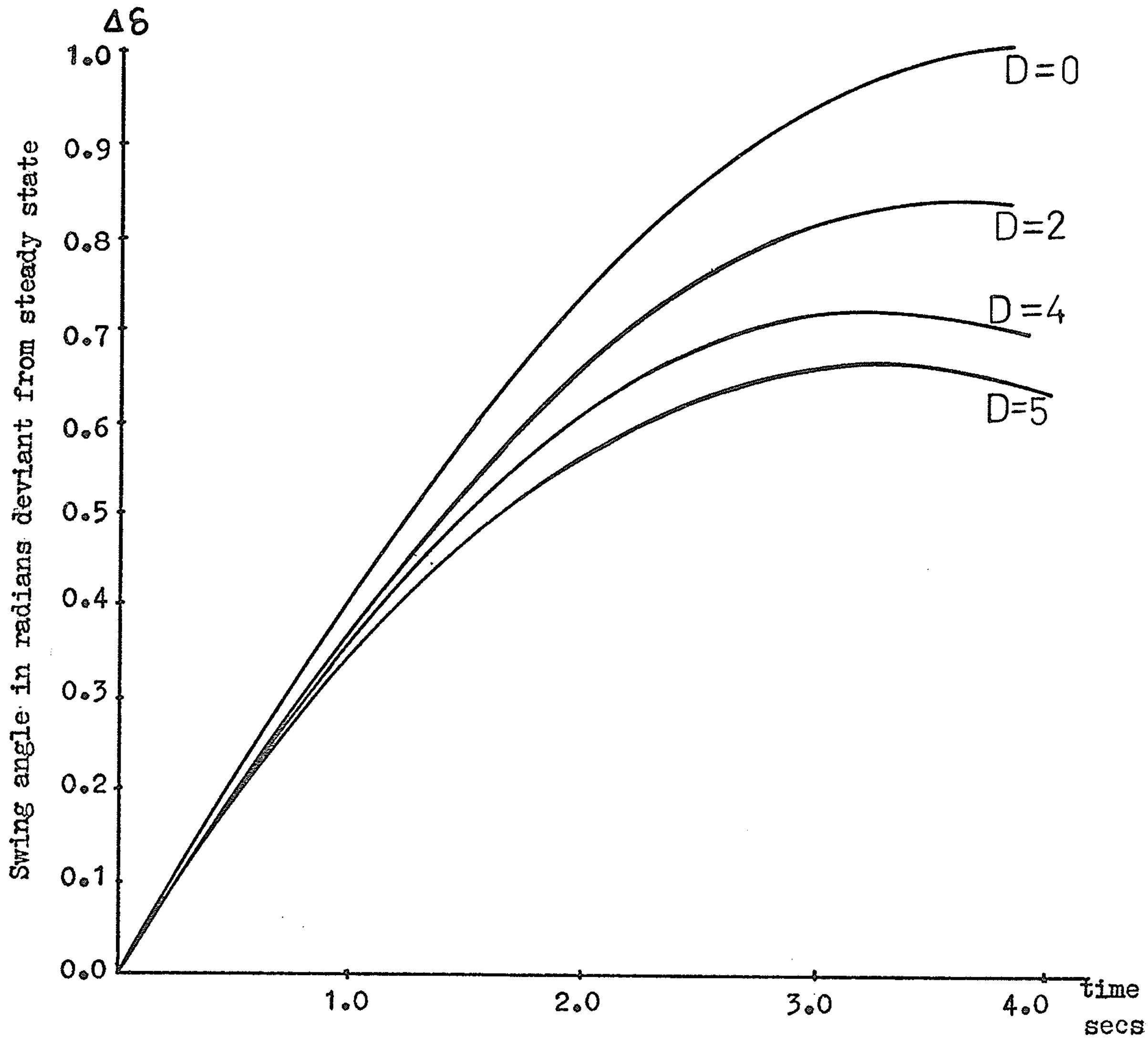


Figure 1.5 Solution of equation 1.10 showing effect of damping on system transient stability.

is maximized. Secondly, the maximum power angle of the first swing across a transmission line following a disturbance is also minimized if damping within the combined total power system is increased. In brief, transient stability across a tie-line is increased with reduced effective line reactance, and/or with increased system damping.

1.4 <u>Variation of tie-line transfer reactance</u>.

The effective series reactance of a tie-line can be reduced by the following ways:

1.4.1 Constructing an additional transmission line in parallel with the existing tie-line(s).

1.4.2 Inserting a series capacitor in the tie-line.

1.4.3 Removing a shunt reactor off the tie-line.

1.4.4 Inserting a shunt capacitor onto the middle of the tie-line.

It is possible to show [1] that by means of a T-to-π transformation, switching a shunt capacitor onto the middle of an ac intertie or switching a shunt reactor off from there is equivalent to insertion of a series capacitor. This insertion and removal technique can control the equivalent tie-line series reactance to improve total system transient stability and damping and is known as "reactive power control."

1.5 <u>Real power damping</u>.

If real power is injected or withdrawn from the power system in a controlled manner to improve transient stability and damping, then this is known as "real power control." Case 2 studied above is an example of real power damping where damping power ΔP_d is actually added or subtracted from the system (see Figure 1.3). An obvious example of real power control is the use of braking resistors near generator terminals. Excitation stabilisation of generators and turbine governor action are also examples of real power control.

Various methods of achieving power system stability and tie-line control are covered in a clear and descriptive manner by E. W. Kimbark in reference [2]. The theory and comments of Kimbark in this paper are important but not duplicated herein, except for this quotation on tie-line control:

> The prevalent opinion seems to be that instability of the interties can be avoided by building stronger interties, that is, more lines or higher voltage lines. This solution is very effective but very expensive. Moreover, it is unnecessary if equally effective but cheaper methods are available. [2]

This dissertation extends Kimbark's discussion on power system stability [2] to particularly examine the effectiveness and benefits of various methods of tie-line control.

1.6 Analytical methods for power system studies.

Analytical tools are necessary for studying a power system during transient and dynamic conditions, to evaluate not only methods of tie-line control, but all aspects of controlling and testing stability of the system. Design must be optimized to ensure stability and reliability and to minimize costs. Unfortunately, no particular model of a power system is perfect because of the complexity of the defining functions and inaccuracy of values of known parameters. It is always good practice to obtain similar results from at least two basically different analytical methods of studying power systems before making conclusions. Analytical studies of power systems including tie-lines can be made by use of the following tools:

1.6.1 Small signal analysis. Linear equations of a power system can be developed, and if suitably reduced, the differential equations can be solved or control theory applied. The simple analysis in sections 1.1 and 1.2 of this chapter is an example of small signal analysis.

1.6.2 Simplified digital analysis. The digital computer can be used to model a reduced power system in simplified form by assuming constant busbar voltages.

1.6.3 Complex digital analysis. Power systems programs for digital computer analysis exist and are large enough to model any expected system. The advantage is the high degree of complexity available, but operating cost is prohibitive.

1.6.4 Analogue computer. The analogue computer can easily solve the approximate differential equations of the power system, but is limited by the size of the system.

1.6.5 Hybrid computer. To obtain advantages of both analogue and digital representation, the hybrid computer can be used. Further developments include the use of the network analyser forming the complex hybrid analogue computer/network analyser.

1.6.6 Direct simulation. Actual small scale models including micromachines, electronic machine models, and a dc link can be used as an effective means of studying the power system, or portions of it.

1.6.7 Electrical network analogue. Passive analogue circuits are used to simulate the power system with linear equations. Active elements using operational amplifiers are used in control loops of governors, dc link, and other control devices. It is a very effective and inexpensive way to determine power system natural frequencies and damping, and to optimize controls. [3]

1.7 Accuracy in power system modelling.

When system design requires many stability studies and cases to be run, it is questionable whether each study be made using a complex digital analysis or expensive power system stability program. It has been shown by Hammons and Winning [4] how mathematical models of the synchronous machine and system under transient conditions compare with actual system performance. Even when the full 5-winding machine equations, including an allowance for saturation are employed, there is a significant difference between the actual test results and the analytical model results for the same disturbance. Furthermore, when many variations of exciter, machine, and governor representation were tested analytically against the actual system, the errors between many simplified system models and the most mathematically accurate model were not as significant as the errors between the accurate model and the actual test performance. No matter how mathematically accurate an analytical power system model may be, there will remain significant error in results compared to actual system transient performance because of the accuracy with which machine and system data is known.

1.8 Power system control studies.

The obvious procedure, therefore, when many stability studies must be undertaken in power system design, is to, firstly, perform all studies on a simplified and cheap analytical model until the optimum design is established, then, secondly, use the complex digital representation to confirm the design. A comparative chart of analytical methods for power system analysis is given in Figure 1.6.

Type of analytical method	Small signal analysis	Simplified digital analysis	Complex digital analysis	Analogue computer	Hybrid computer	Direct simulation.	Electrical network analogue.
Advantages	Low cost. Can use standard control techniques.	Low cost.	Very accurate for any non-linear system.	Easily solves differential equations.	Retains the advantages of both digital and analogue calculations.	Most useful for dc link model.	Low cost for comprehensive system representation.
Disadvantages.	Effect of non-linear components are lost	Restricted representation of power system.	Relatively high cost to operate.	Restricted representation and accuracy.	Restricted representarion.	Ac system representation not easily accomodated.	Based on linear equations.
Relative effectiveness.	Not effective unless used with familiarity.	Effective only when models are realistic.	Very effective.	Effective for reduced models but accuracy reduced.	Effective for reduced power system models.	Very effective for dc studies or studying system elements	Very good for ac system controls optimizing.
Cost	Inexpensive	Not expensive if used with experience.	Very high cost.	For repeated cases, much cheaper than digital.	Usually more expensive than analogue.	High initial cost but cheap to operate.	Inexpensive if many cases are to be studied.
Use	To indicate approximate stability and form of ac system control.	To indicate approximate stability and trends. To test controls.	Accurate analysis of power system verifying design.	Solving differential eqns, determining stability and control design.	Improves the effectiveness of analogue computer.	Dc system analysis and controls design.	Determining ac system controls by trial and error.

Figure 1.6 Comparison of relative merits of analytical methods for power system control studies.

1.9 Analytical methods used in this study.

Analytical methods used in this dissertation to show the capability of various tie-line control techniques are:

1.9.1 Small signal analysis. In sections 1.1 and 1.2 of this chapter two linear mathematical cases illustrate how tie-line control can be attained, *i.e.*, through reactive power control and through real power control.

1.9.2 Simplified digital analysis. A three machine, undamped, non-linear power system model was developed and programmed on digital computer. This model enabled tie-line controllers to be added. Because the system was basically undamped, any improvement in transient stability and damping was entirely a result of a tie-line controller. Consequently, a comparison of the effectiveness of various tie-line control techniques could be made. More information on this three-machine, non-linear model is found in Appendix I.

1.9.3 Complex digital analysis. A general digital non-linear power system stability program entitled DENA was developed to analyze a complex power system. This program (DENA) is specifically suited for tie-line control analysis, firstly, because its algorithm is such that any transmission line series reactance or other power system reactance can vary continuously with time without the need of matrix inversion or replacement of admittance or impedance matrices, and, secondly, control functions are easily added. A twelve-machine power system approximating Manitoba, Saskatchewan, and the United States systems was obtained from Manitoba Hydro and fed into this program, and the effects of tie-line control on a "real" system were studied. More information on DENA is found in Appendix II.

1.10 Conclusions.

1.10.1 The stability of systems interconnected through a tie-line can be improved by reducing effective tie-line series reactance and by increasing system damping.

1.10.2 It is not necessary for power system analytical models to have great mathematical accuracy to obtain significant results in transient stability and control studies.

1.10.3 For this thesis, three analytical methods are found to be adequate to determine effectiveness of tie-line control techniques.

1.10.4 Optimizing power system control functions may require trial and error analysis which can only be done efficiently if an adequate, cheap to run power system model is used. The complex digital power systems program is necessary as a final check on design.

CHAPTER 2

RATING OF REACTIVE POWER TIE-LINE CONTROLLERS

2.0 Series and shunt reactive power control of tie-lines.

Improvement of power system stability can be effected by controlled variation of tie-line series or shunt reactance. As mentioned in the previous chapter, switching a capacitor in series with the transmission line is equivalent to switching out a shunt reactor or switching in a shunt capacitor. In this chapter a method is outlined for evaluating and comparing the maximum reactive MVAR capacity for both series and shunt controllers based on transient stability requirements. However, the methods of switching or varying the controlling reactance are included in chapter 3.

2.1 Transmission line representation.

If a transmission line is less than one-hundred miles in length, it can be represented by a simple "equivalent π" single phase circuit. The series impedance component of the equivalent π is a linear function of the per mile impedance and the admittance shunt component at each end of the line is a linear function of the per mile admittance. However, the transmission line is considered "long" when greater than one-hundred miles in length, and the equivalent π

representation is valid only if the series and shunt components are modified to allow for transmission propagation phenomena. If the transmission line series impedance is Z_1 ohms per mile, the shunt admittance is Y_1 mhos per mile and the transmission line section is ℓ miles long, then the equivalent π line components for short and long lines are shown in Table 2.1

For the purpose of this dissertation, the following two approximations are made to simplify presentation and clarify methods:

a.) Short line equivalent π sections are used to build up a transmission line.

b.) Lossless transmission lines only are considered.

The error in using short line π equivalent sections is minimized when several such sections are used in cascade to represent the long transmission line. The effect of line losses is also minimized when line reactance is significantly greater than line resistance.

Equivalent π line components	Transmission line less than 100 miles	Transmission line greater than 100 miles
Series impedance component Z_L	$Z_1\ell$	$\sqrt{\frac{Z_1}{Y_1}}\cdot\text{Sinh}(\sqrt{Z_1Y_1}\,\ell)$
Shunt admittance component $\frac{Y_L}{2}$	$\frac{Y_1\ell}{2}$	$\dfrac{\text{Cosh}(\sqrt{Z_1Y_1}\,\ell)-1}{\sqrt{\frac{Z_1}{Y_1}}\cdot\text{Sinh}(\sqrt{Z_1Y_1}\,\ell)}$

Table 2.1 Equivalent π line components for short and long transmission lines.

2.2 Series control.

Use of switched series capacitors in tie-line control has already been investigated. [1], [5] To conduct economic studies involving effect of series capacitors in transmission lines, capacitor MVAR rating must be determined. Capacitor rating can be easily resolved from the graph of Figure 2.1 which is developed from basic equations as follows. Let the total effective series inductive reactance of the transmission line (including system Thevenin reactances at each end) be X_L per unit, and the Thevenin voltage sources at each end of the line be both 1.0 per unit with a phase angle difference of δ degrees. Series capacitors are placed in the transmission line with a total capacitive reactance of X_C per unit. The effectiveness of the series capacitors to act as compensators is dependent upon their position along the line as well as the position of any shunt reactive devices. An "efficiency" factor 'K' can be defined [6] so that with the series capacitance in the transmission line, the total effective series reactance of the whole line X_T is defined as

$$X_T = X_L - KX_C \qquad (2.1)$$

where K = "efficiency" factor which can vary between 0.5 and 1.5.

From simple ac circuit theory, the per unit reactive power (MVAR) developed across an inserted series capacitance of X_C per unit capacitive reactance is

$$\text{MVAR} = (\text{Line current})^2 X_C$$

$$= \frac{4 \sin^2(\delta/2)}{X_T^{\ 2}} X_C$$

which can be rearranged so that

$$\text{MVAR}.X_L.K = \frac{4 \sin^2(\delta/2)}{\left[1 - \frac{KX_C}{X_L}\right]^2} \cdot \frac{KX_C}{X_L} \qquad (2.2)$$

Equation 2.2 enables percentage effective series capacitive reactance (KX_C/X_L x 100) to be plotted against the product of the per unit series capacitor reactive power, line reactance X_L and "efficiency" factor K for various phase angles of δ across the transmission line. (See Figure 2.1.)

For an example, the total effective inductive reactance of a transmission line (including Thevenin source reactance at each end) is X_L = 0.927 per unit, and 25% series capacitive reactive compensation is being considered for series capacitor switching. Consider that the efficiency of compensation K is determined to be 0.9. Consequently, the percentage effective series capacitive reactance is

$$K\frac{X_C}{X_L} \times 100 = 0.9 \times 25 = 22.5$$

From Figure 2.1, for $\delta = 90^{\circ}$, the product $MVAR \cdot X_L \cdot K = 0.73$.
Therefore, $MVAR = \frac{0.73}{X_L \cdot K} = \frac{0.73}{0.927 \times 0.9} = 0.875$ per unit.
This is the series capacitor rating for $\delta = 90^{\circ}$

However, operation at 90° phase angle across the transmission line is usually only a transient condition. Therefore, the series capacitor can be derated depending on its overload capability. Possibly, the series capacitor could be derated to one-half its 90° rating, so that the continuous rating would be 0.437 per unit (MVAR). Contrast this rating with the 25% series capacitor rated to withstand only a steady state 30° phase angle across the total effective line. From Figure 2.1, the 30° steady state rating is found to be 0.12 per unit. If the series capacitor can transiently withstand twice its steady state rating, then from Figure 2.1 it can be found that the 0.12 per unit rating of series capacitor can just survive a transient power angle swing from 30° to 45° maximum across the transmission line.

This example illustrates the limitation of series capacitors in tie-lines. Further problems are:

2.2.1 The problem of optimizing the short time overload capability of capacitors to withstand transient power angle swings.

2.2.2 Capacitor protection devices tend to remove the

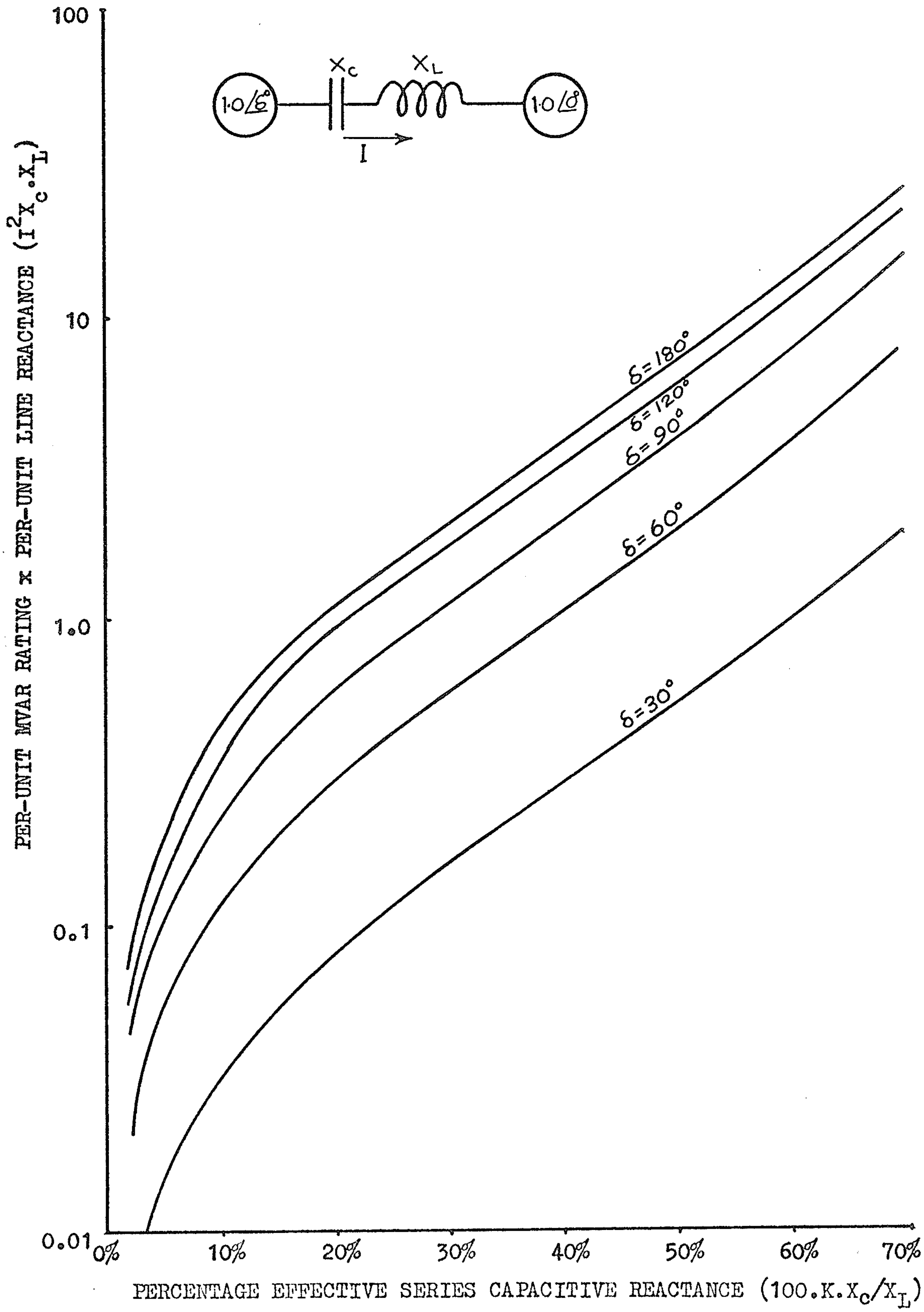


Figure 2.1 Per unit rating of series capacitance as a function of line reactance X_L, power angle δ, and % series capacitive reactance.

series capacitor at a time when it is most needed, i.e. the peak of the transient swing.

2.2.3 The availability of fast opening and reclosing switches necessary to make capacitor insertion effective and economical.

2.2.4 Determining the advantage if any, of series capacitor insertion over series compensation.

2.3 Practical application for series capacitor switching.

The best application for series capacitor control is to increase tie-line stability when one of two parallel lines trips out on fault. This is the case considered by Smith in reference [5]. (See Figure 2.2)

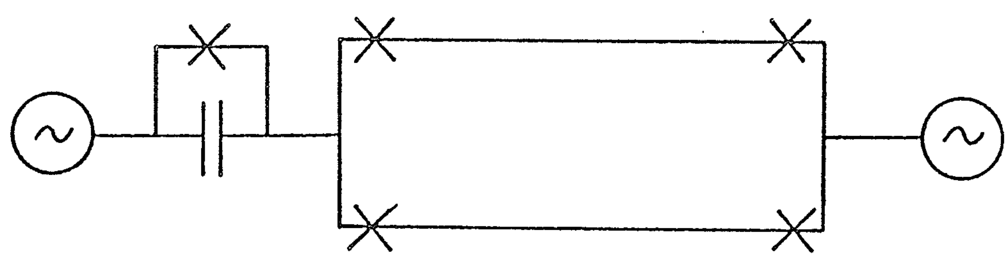


Figure 2.2 Improving stability of a parallel line intertie with series capacitor switching.

The effectiveness of a tie-line controller can be gauged by the interconnection power angle diagram. This is based on equation 1.1 and is plotted as power transfer P_L vs. voltage phase angle or power angle δ

across the total effective tie-line reactance. For the example of Figure 2.2, the power angle diagram is drawn in Figure 2.3 showing effect of two lines in, one line out, and one line out with series capacitor inserted.

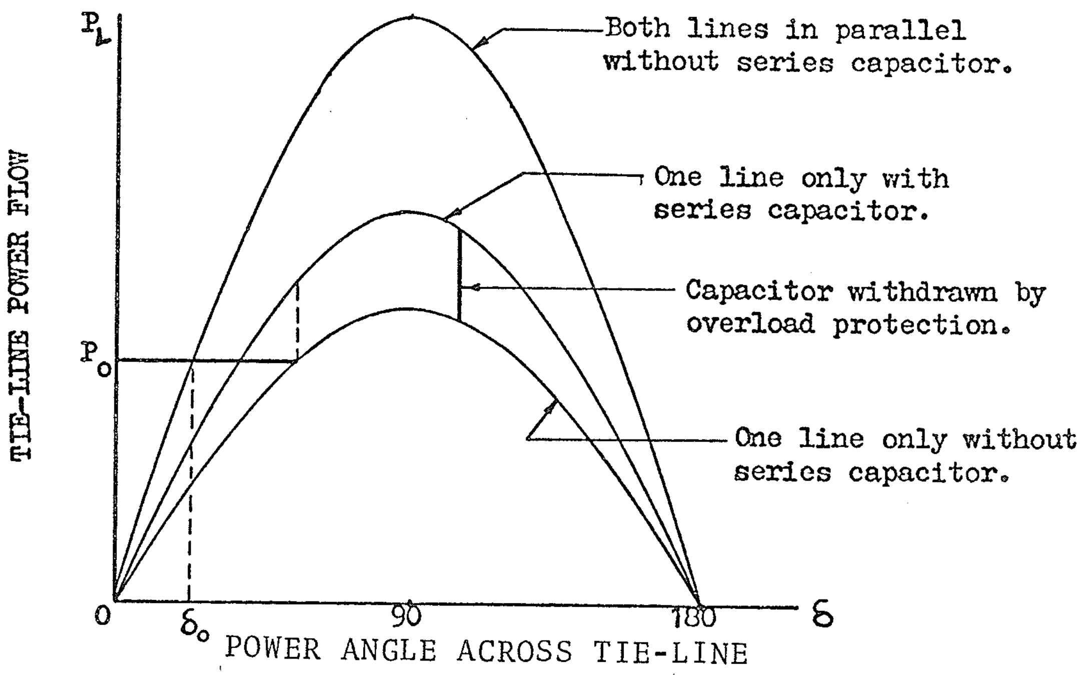


Figure 2.3 Power angle diagram of two circuit ac intertie with switched series capacitors.

Transient stability is improved across the tie-line if the peak power value of the power angle characteristic is effectively increased. It can be seen from Figure 2.3 that insertion of the series capacitor when only one line is in service significantly increases the peak value of the power angle characteristic for that one line. Stability evaluation of the tie-line for any particular transient disturbance and switching operation can be determined using the equal area criterion.

2.4 Representation of tie-lines for shunt control.

The representation of a transmission line as just a series inductive reactance is inadequate when shunt reactances distributed along the line are to be used for controlling the line equivalent transfer impedance. The power angle expression for a transmission line, including the Thevenin source impedances and voltages is:

$$P = \frac{E_1 E_2 \sin \delta}{X_T} \qquad (2.3)$$

where E_1, E_2 are Thevenin voltage magnitudes at each end of the line.

δ = total power angle between E_1 and E_2

X_T = equivalent line impedance.

The easiest method to determine X_T for a transmission line is using A,B,C,D constants which enable the distributed nature of the line to be accurately represented. For the examples included herein, the transmission line will be represented by an equivalent circuit, with A,B,C,D constants applied to each segment.

Consider the example of a long lossless transmission line having series inductive reactance jX_L per unit and total shunt capacitive admittance of jY_L per unit. In addition, a shunt tie-line controller is fixed at the line mid-point having a maximum capacitive admittance of jY_C per unit. The line approximate equivalent circuit is formed from two π equivalent line sections as shown in Figure 2.4.

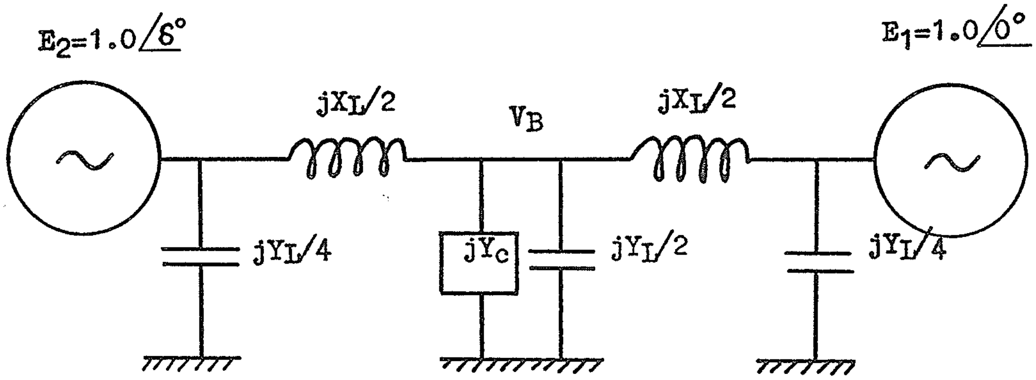


Figure 2.4 Equivalent circuit of transmission line with shunt controller.

Shunt control is effective when a "variable" or switched reactance capable of operating in both capacitive and inductive modes is positioned at the line centre (or for very long transmission lines, two or possibly three shunt controllers will be needed distributed equally spaced along the line at third or quarter points respectively). During fault conditions when the transient power angle δ increases across the line, it is desirable to force the mid-point voltage V_B high by increasing shunt capacitance. Consequently, the transfer impedance of the transmission line is reduced, and the stability limit increased. Unfortunately, the mid-point voltage or Ferranti over-voltage must be limited for insulation reasons, and so the performance of shunt control is inhibited.

From Figure 2.4, let the total shunt admittance at the mid-point of the transmission line be jY_S.

Therefore, $$jY_S = jY_C + \frac{jY_L}{2} \text{ per unit} \tag{2.4}$$

The transmission line including shunt controller is represented by A,B,C,D constants thus:

$$\begin{bmatrix} A_o & B_o \\ C_o & D_o \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{jY_L}{4} & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{jX_L}{2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jY_S & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{jX_L}{2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{jY_L}{4} & 1 \end{bmatrix} \tag{2.5}$$

Solving this equation for B_o gives the equivalent line impedance which is

$$B_o = \frac{jX_L}{4}\left[4 - X_L Y_S\right] \tag{2.6}$$

The power angle relationship for the transmission line is found by substituting equation 2.6 into 2.3:

$$P = \frac{4E_1E_2 \text{ Sin } \delta}{X_L\left[4 - X_LY_S\right]} \tag{2.7}$$

Using this technique, it is possible to solve the equivalent line impedance for two and three or more shunt reactances distributed along the transmission line.

However, consider just the single controller at line centre as shown in Figure 2.4. By ac circuit theory, the mid-point voltage magnitude V_B is found to be

$$V_B = \frac{2\sqrt{2}\sqrt{1 + \text{Cos } \delta}}{\left[4 - X_LY_S\right]} \text{ per unit} \tag{2.8}$$

This expression assumes the magnitudes of the end Thevenin voltages remain fixed at 1.0 per unit each. From equation 2.8 it is possible to determine the reactive power rating of a mid-point shunt controller. From equation 2.8.

$$X_LY_S = 4 - \frac{2\sqrt{2}\sqrt{1 + \text{Cos } \delta}}{V_B} \tag{2.9}$$

Taking into account equation 2.4, then

$$X_LY_C = 4 - \frac{2\sqrt{2}\sqrt{1 + \text{Cos } \delta}}{V_B} - \frac{X_LY_L}{2} \tag{2.10}$$

If $V_B = 1.0$ per unit, then $Y_CV_B{}^2 = Y_C$ per unit reactive power of a shunt admittance Y_C for a phase angle δ.

Thus equation 2.10 becomes

$$\text{(MVAR of controller)}.X_L = 4 - 2\sqrt{2}\sqrt{1 + \cos\delta} - \frac{X_L Y_L}{2} \qquad (2.11)$$

Equation 2.11 is plotted in Figure 2.5 as MVAR.X_L vs. δ, for various values of $\frac{X_L Y_L}{2}$. Equation 2.11 or the graph in Figure 2.5 enables the admittance and rating of a shunt controller in a transmission line to be determined to maintain the volts at the controller of a desired value for various power angles across the transmission line. This is important when comparisons are to be made with series compensated lines.

2.5 Rating the shunt controller.

Consider the following example to illustrate how the steady state reactive power rating of a shunt controller can be determined. A 500 kV single circuit line is four-hundred miles long. The series uncompensated line reactance including Thevenin reactances at each end is $X_L = 0.927$ p.u. (per unit). The total distributed capacitive reactance is $\frac{1}{Y_L} = 1.0$ p.u.

Therefore, $\frac{X_L Y_L}{2} = \frac{0.927 \times 1.0}{2} = 0.464.$

If the transmission line is stably loaded when the power angle $\delta = 30^{\circ}$, then from equation 2.11 or Figure 2.5, the reactive power of the shunt controller to maintain 1.0 p.u. volts at line centre is -0.4 p.u.

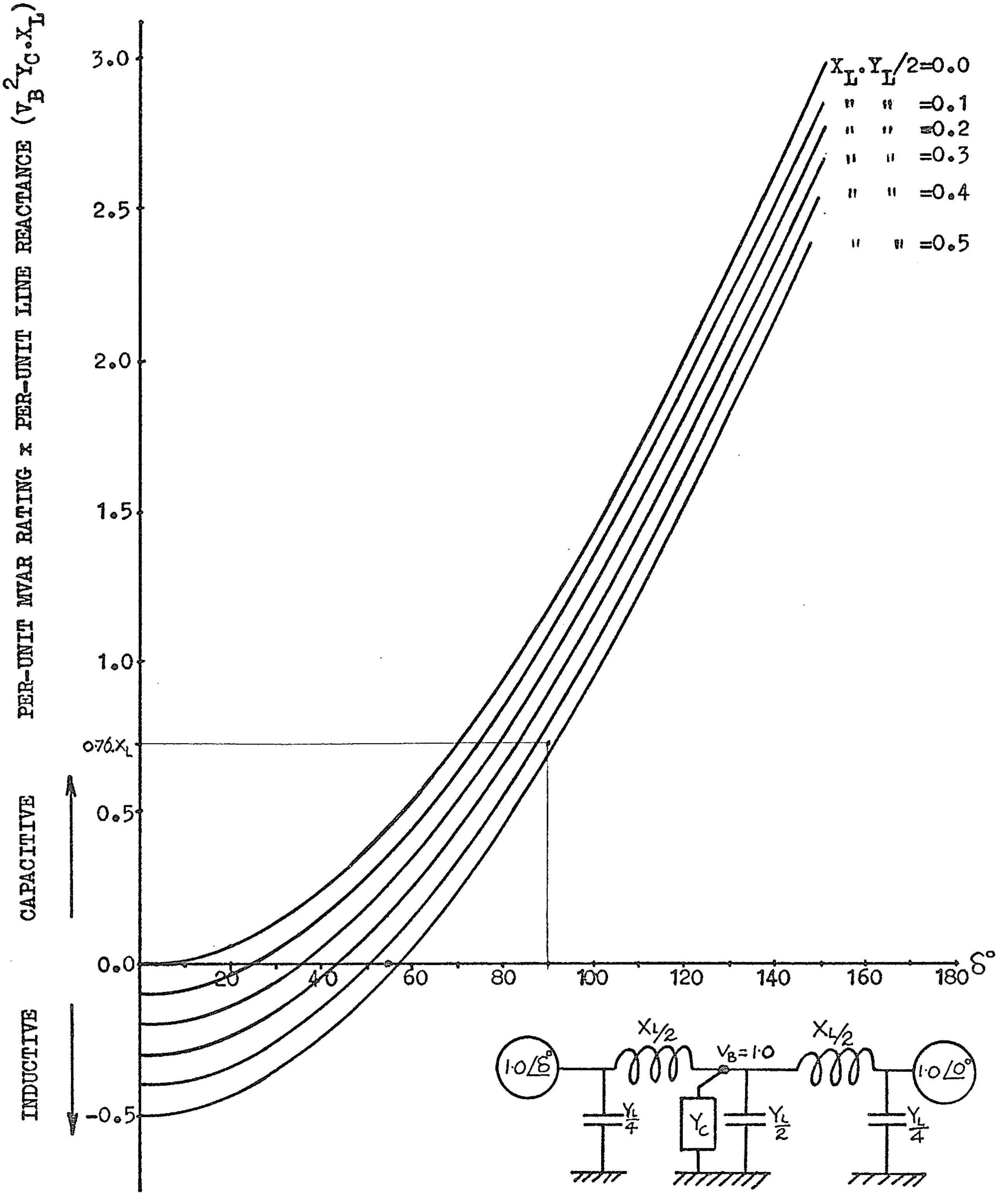


Figure 2.5 Per unit reactive power of mid-point shunt reactance $1/Y_C$ to maintain mid-point volts $V_B = 1.0$ p.u. for varying power angle δ, and as a function of line reactance X_L, and line admittance Y_L.

reactive power. The negative sign indicates the shunt reactance of the controller must be inductive for this loading and condition of the line, and is just an indication of the normal inductive shunt compensation needed at line centre.

However, the operation of an effective shunt controller is such that the full load steady state power angle across the transmission line can be increased still maintaining transient stability. Consider a shunt controller which can effectively maintain mid-line volts at 1.0 per unit during transient swings up until the total power angle across the transmission line reaches $\delta = 90^{\circ}$. Assume the steady state operating power angle across the transmission line can be increased to $\delta = 55^{\circ}$. From equation 2.11 or from the graph of Figure 2.5, the shunt controller at line-centre must be rated at 0.0 per unit reactive power for $\delta = 55^{\circ}$, but for $\delta = 90^{\circ}$, the rating of the shunt controller must be 0.76 p.u. capacitive.

This example illustrates how the shunt controller must be capable of varying quickly, and if it is to replace series compensation must operate in the inductive mode for small power angles and in the capacitive mode for large power angles.

2.6 Comparison of series and shunt reactive controllers.

An equivalence between series and shunt control and compensation can be made by equating equations 1.1 and 2.7, i.e.

$$P = \frac{4E_1 \cdot E_2 \sin \delta}{X_L(4 - X_L Y_S)} = \frac{E_1 \cdot E_2 \sin \delta}{X_L - X_C} \qquad (2.12)$$

from which

$$\frac{4X_C}{X_L} = X_L Y_S \qquad (2.13)$$

However, this relationship does not correctly apply when the shunt admittance is limited by maximum allowable line volts. When comparing reactive power requirements between series and shunt control, the following points should be considered:

2.6.1 When series and shunt reactive ratings to withstand large transient power angle swings are being determined, it should be realized that both reactors and capacitors are capable of withstanding transient over-loads. Consequently, the capacitance rating indicated by Figures 2.1 and 2.5 for maximum peak power angles can possibly be substantially derated.

2.6.2 The effectiveness of series capacitors is dependent on their positioning along the transmission line and also on the position of normal line shunt inductive compensation reactors. [6]

2.6.3 The effectiveness of shunt controllers is also dependent upon their position along the line and whether there is line series compensation. Ideally, the shunt controller performs best at the line centre and without any series compensation.

2.6.4 A disadvantage of shunt control is that its transient capability is reduced when the mid-point volts V_B is limited to, say, 115% of rated volts because of insulation requirements and possible corona losses.

2.6.5 An advantage of shunt control is its impunity from line faults, whereas, series capacitors can be very sensitive to line faults and must be well protected.

It has been the objective of this chapter to present a simple method to determine ratings of series and shunt capacitors for reactive power tie-line control. Evaluating the performance of tie-line controllers to meet a specified transient stability limit will be covered in following chapters as will the techniques for switching or varying shunt reactance to obtain necessary control.

CHAPTER 3

OPERATION AND PERFORMANCE OF REACTIVE POWER TIE-LINE CONTROLLERS

3.0 Reactive power tie-line controllers.

The operation and performance of series and shunt reactive power controllers will be examined and compared in this chapter. The various controllers studied are listed as follows:

3.0.1 Switched series capacitors.

3.0.2 Switched shunt reactors and capacitors.

3.0.3 Static compensation using saturable reactors.

3.0.4 Variable reactors.

3.0.5 Short circuit limiting coupling.

Each of these tie-line controllers affects transfer impedance changes in tie-lines by varying or switching capacitive and/or inductive reactances. The techniques for varying reactance are:

a.) fast acting switches including thyristors

b.) operating reactors in saturation.

To obtain a comparison of performance between the tie-line controllers, a three machine power system was modeled on digital computer. The exact network equations were used for a load flow at each computational time step, but each of the three machines were represented as voltage behind reactance without damping.

With no inherent damping in the model, it was possible to compare the effectiveness of each tie-line controller as the only damping element. (See Figure 3.1.)

A three machine model was chosen because two swing harmonics will exist during dynamic operation. This case is more "realistic" than the usual one machine to infinite busbar case. A fault on the system was selected to just maintain stability with no tie-line controller functioning. Further information on the digital program of this model is given in Appendix I.

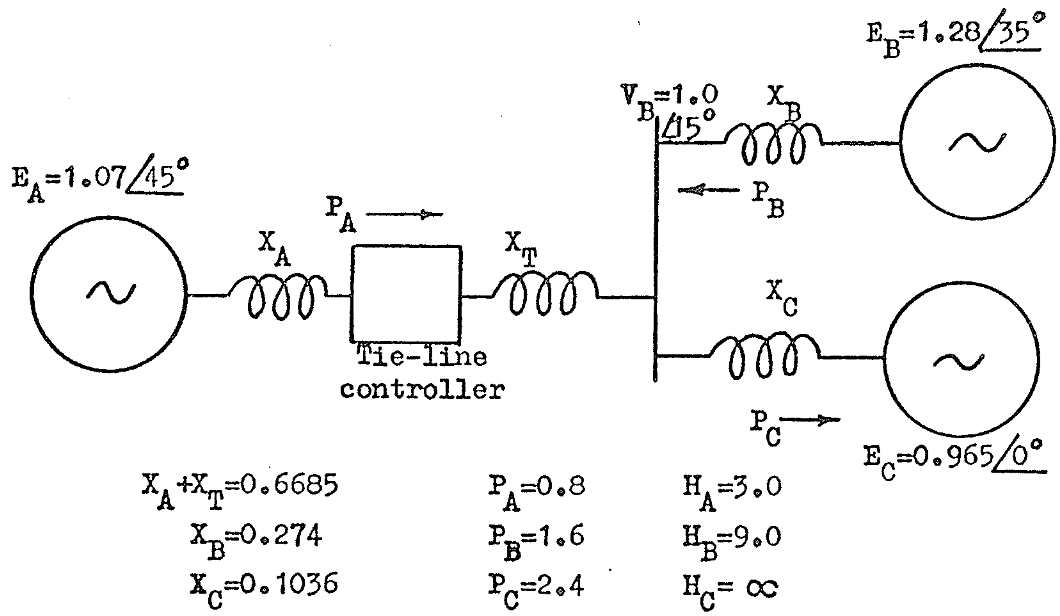


Figure 3.1 Three machine power system model with tie-line controller and steady state operating condition.

3.1 Switched series capacitors.

Inserting a series capacitor in a tie-line during a transient upswing effectively strengthens the tie-line so that the diverging power systems on each end are held together with greater stiffness. (See Figures 2.2 and 2.3.) For the three machine power system model in Figure 3.1, elementary control logic was used to insert the capacitor in the tie-line with the power angle across it increasing and to remove the capacitor as the power angle across the line decreased. The disturbance was initiated by a three phase fault to ground of 0.12 seconds duration at machine C. This fault duration was selected to just maintain stability. The dynamic swings of the voltage phase angle of machine A compared with machine C (infinite busbar) are shown in Figure 3.2 for four cases, each subject to the same fault. These cases are:

Case 1. Undamped swings of machine A without tie-line control.

Case 2. Control with series capacitance = 0.054 per unit, or approximately 7% series capacitive reactance.

Case 3. Control with 0.118 per unit or approximately 15% series capacitive reactance.

Case 4. Control with 0.167 per unit or approximately 22% series capacitive reactance.

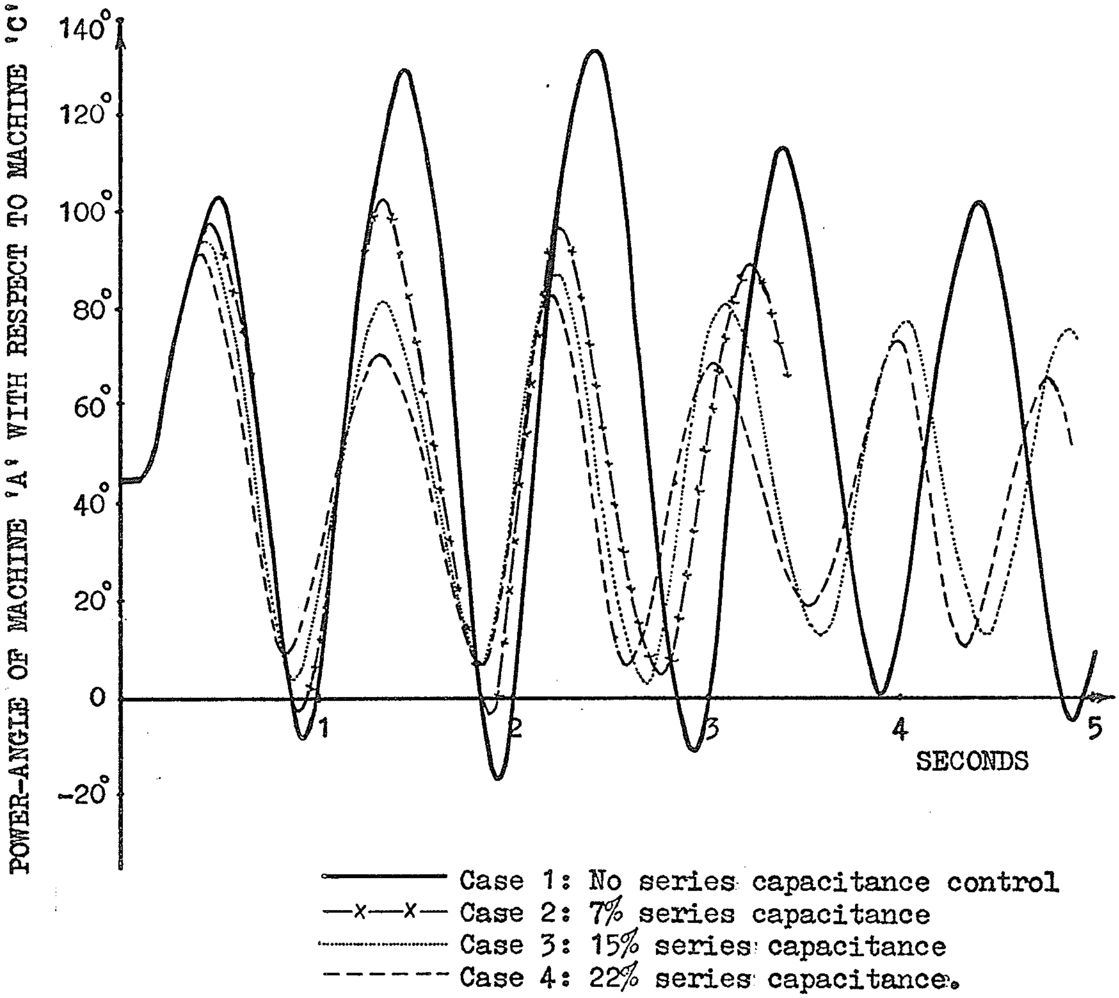


Figure 3.2 Effect of switched series capacitance tie-line control.

It can easily be seen in Figure 3.2 that with increased value of the switched series capacitance in the tie-line to machine A, there is a corresponding improvement in transient stability and damping. Smith, in the conclusion of reference [5] states:

> The transient insertion of ten-percent series capacitive reactance can produce spectacular increases in transient stability bringing the

> power limitation due to transient stability to nearly the post transient steady state stability limit. [5]

The results shown in Figure 3.2 do not substantiate such spectacular improvements in transient stability for just ten-percent series capacitive reactance. The fact that more than ten-percent series capacitive reactance is needed for effective tie-line control was observed in stability studies of a "real" system model. Tie-line control was studied with the model depicted in Figure 3.3 approximating the Saskatchewan-Manitoba-U.S.A. power systems with the DENA digital program (see Appendix II). With a series capacitor tie-line controller in the transmission line between Brandon and Boundary Dam, results can be summarized as follows.

3.1.1 For any significant improvement in combined Manitoba and Saskatchewan stability, the series capacitor should be rated at least 25% series reactance.

3.1.2 The short time rating of the series capacitor should be sufficient to allow large transient power angle swings across the tie-line - for swings of 90° or possibly 130°.

3.1.3 The actual capacitive reactance value and rating of the series tie-line controller would need to be determined from stability studies and economic appraisal of performance and cost.

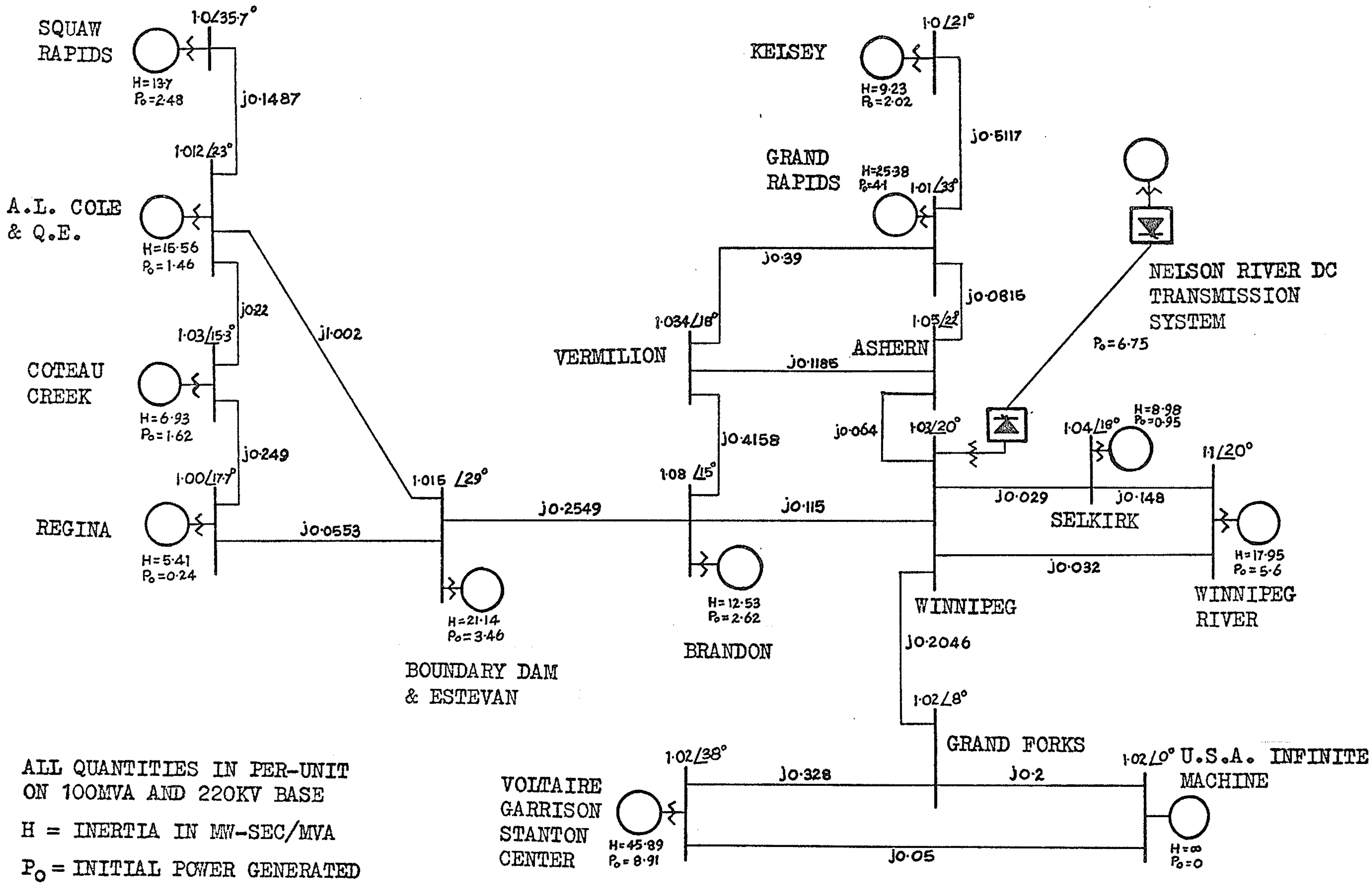


Figure 3.3 U.S.A.-Manitoba-Saskatchewan power system model

3.1.4 The cheapest way of strengthening the Brandon-Boundary Dam tie-line would be optimum excitation stabilization of the Brandon and Boundary Dam generators, with a possible feedback signal to the exciters derived from tie-line current. (Tie-line current is a function of voltage phase angle across the tie-line.)

A better application for series capacitor insertion is in the tie-line between Manitoba and the U.S.A. The infinite busbar quality of the U.S.A. power system acts as an anchor for Manitoba, and reducing the tie-line reactance serves to steady the power angle swings of Manitoba. But again, studies indicate more than 25% series capacitive reactance in this tie-line would be needed for effective stability improvement. With 30% series capacitor control in the Manitoba-U.S.A. tie-line and a fault at Winnipeg equal to the temporary loss of a pole on the dc link of 225 MW (no damping control on the dc link), swing curves with and without a switched capacitor are shown in Figure 3.4. The improvement in stability and damping is obvious.

3.2 Series optimal control.

Theoretical studies have been undertaken using optimal control techniques to illustrate how a power system can be restored to its steady state operating condition in minimum time after a transient disturbance. [7]

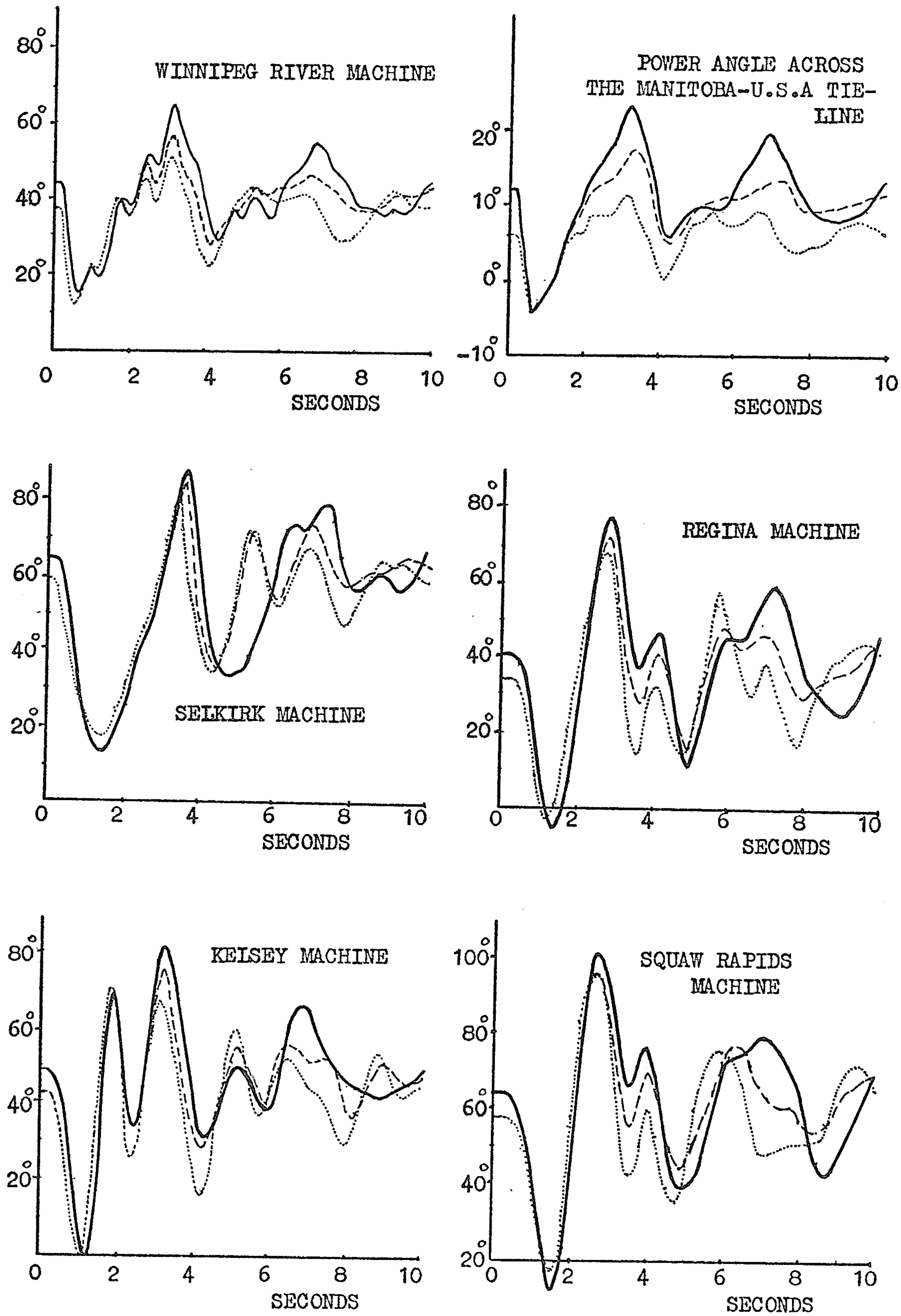


Figure 3.4 Swing curves of U.S.A.-Manitoba-Saskatchewan power system model with a 0.5 second temporary block of one dc link pole (225 MW) and no dc link ac system damping. Cases are; ——— normal operation, - - - - switched capacitor controller in Manitoba-U.S.A tie line, ... extra Manitoba-U.S.A tie-line.

The principle of operation is simple: following a transient disturbance, the operating power angles of the power systems at each end of a tie-line tend to swing apart. Stability is increased using tie-line control techniques to minimize the peak power angle swing. With stability maintained the power systems swing back toward the initial steady state operating condition. It is during this swing back that optimal control is achieved. At a computed time during the backward swing, series capacitance is inserted in the tie-line having more than 100% capacitive reactance, say, 200% capacitive reactance. The effect of this action is to suddenly invert the power angle characteristic of the tie-line so that power flow through the intertie is reversed. See power angle characteristic Figure 3.5.

Optimal control is achieved when areas $a_1 = a_2$. Theoretically, the steady state operating condition will remain restored without any further oscillation.

Comments on this method of optimal control are:

3.2.1 There is a possibility of high harmonic and subharmonic overvoltages with compensation greater than 100%.

3.2.2 The performance of fast acting switches or circuit breakers may not be adequate to provide the exactness of operation required.

Possibly, it is not necessary to resort to greater than 100% series capacitive reactance to achieve

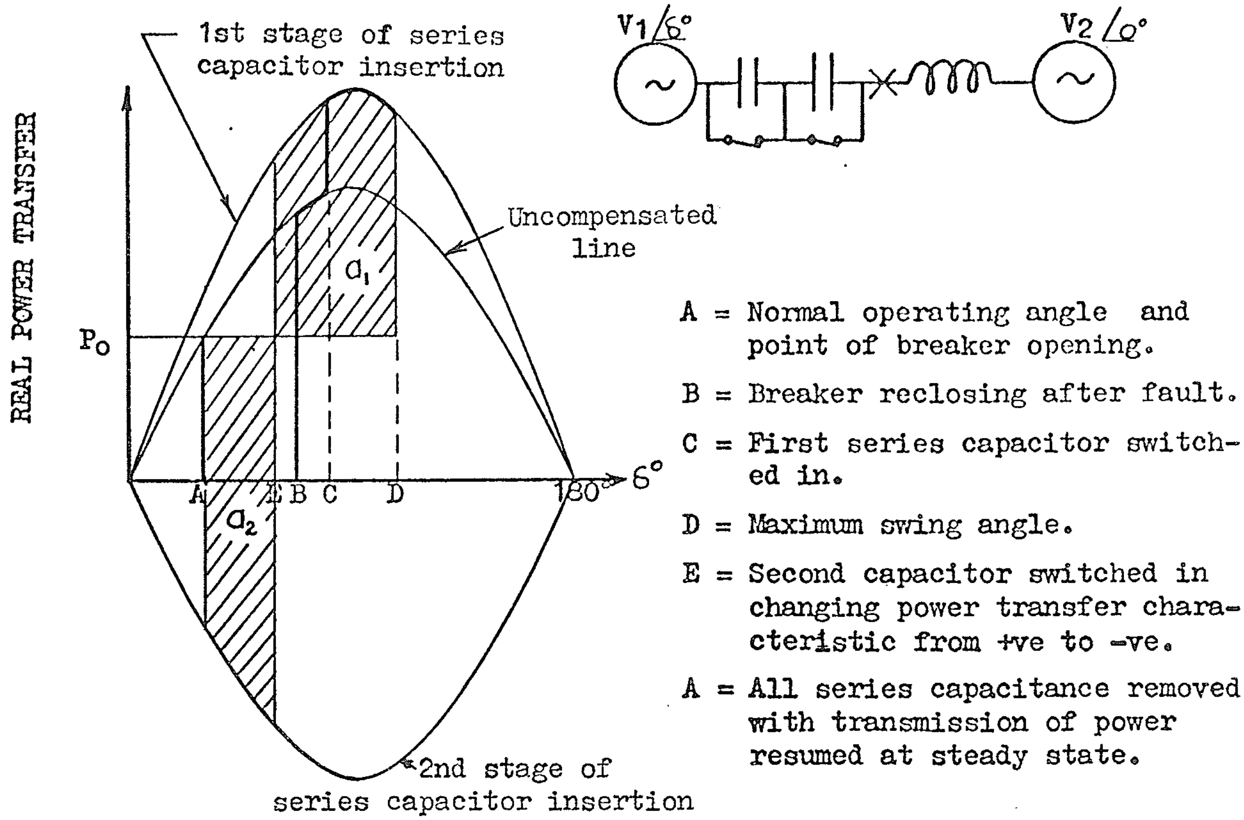


Figure 3.5 Power angle characteristic with optimal control using negative line reactance characteristic.

optimum control. The question is raised; instead of switching in extra series capacitance during the backswing, giving a negative power angle characteristic, why not just open and reclose a line circuit breaker? That is, remove the tie-line controller just after the peak of the first transient swing, and then, for a short interval during the backswing, open and reclose the line circuit breaker. The power angle diagram for this case would be as in Figure 3.6.

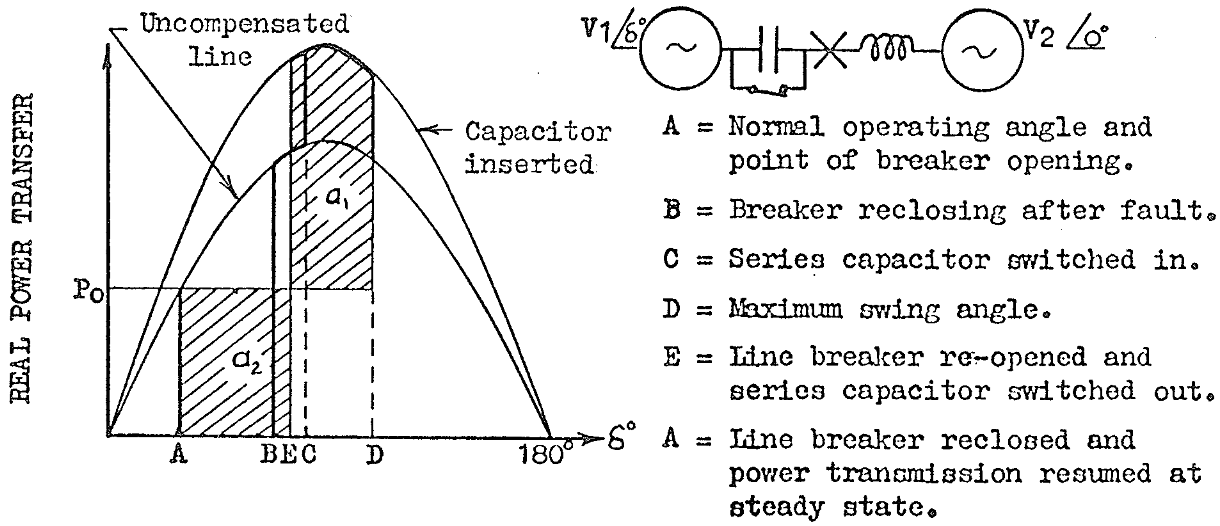


Figure 3.6 Power angle characteristic with optimal control using temporary line removal and capacitive switching.

The advantage of this method of optimal control over the negative line reactance method is economics. If fast auto-reclosing circuit breakers are being used on the tie-line, then cost of control equipment to initiate breaker operation on the backswing of large transient disturbances should be less than the cost of capacitors and switch.

Furthermore, the possibility of accurately computing the exact moment of breaker initiation is doubtful when considering the uncertainty to which the power system parameters are known. For example, machine interactions at each end of the tie-line and the effect of exciter dynamics. Consequently, just a standard auto-reclosing breaker operation in the middle of the backswing from large transient disturbances may be just as effective as a "computed" optimal control system.

3.3 Switched shunt reactors and capacitors.

Many long distance high voltage transmission lines require shunt compensation for an acceptable balance of reactive power generation and line voltage profile. The amount and type of shunt compensation (i.e. whether inductive or capacitive) is dependent on the transmission line design. It is possible that some EHV transmission lines require inductive shunt compensation to be switched in even when operating at maximum designed steady state load. If a tie-line requires inductive shunt compensation at maximum load, it is an inexpensive and simple matter to provide controls which on sensing a transient disturbance, initiate the fast removal of shunt reactors during the first upswing.

Consider an example of the 500 kV, 400 mile single circuit tie-line studied in Chapter 2, section 2.5. The power base is 1000 MW. Total series uncompensated line reactance $X_L = 0.927$ p.u., and the total distributed capacitive reactance is $\frac{1}{Y_L} = 1.0$ p.u.

Using the equivalent circuit for a long transmission line as in Figure 2.4, it was found in section 2.5 of Chapter 2 that if the transmission line was loaded with a power angle of $\delta = 30^{\circ}$, that the effective shunt inductive reactive power at the line centre must be 0.4 p.u.

On sensing a transient disturbance or increase in power angle across the transmission line, it is possible to remove the inductive shunt compensation and increase the power transfer capability of the transmission line.

The power angle relationship is found from Equation 2.7 and with the shunt inductance in is:

$$P = 1.12 \sin \delta$$

However, if the shunt inductive compensation is removed so that the line charging capacitance raises the line volts, the power transfer capability is

$$P = 1.22 \sin \delta$$

Thus, it can be seen that removing the shunt compensation increases the power angle curve as shown in Figure 3.7. The amount of inductive shunt reactance that can be removed, or shunt capacitance that can be inserted, is limited by the maximum allowable line voltage.

By continued removal of shunt compensation during upswings of power angle across the tie-line and re-insertion during backswings, it is possible to achieve not only improved transient stability, but also damping. This is demonstrated using the three machine model shown in Figure 3.1 and Appendix I. The shunt controller consisted effectively of simple logic switching shunt inductance out and shunt capacitance in

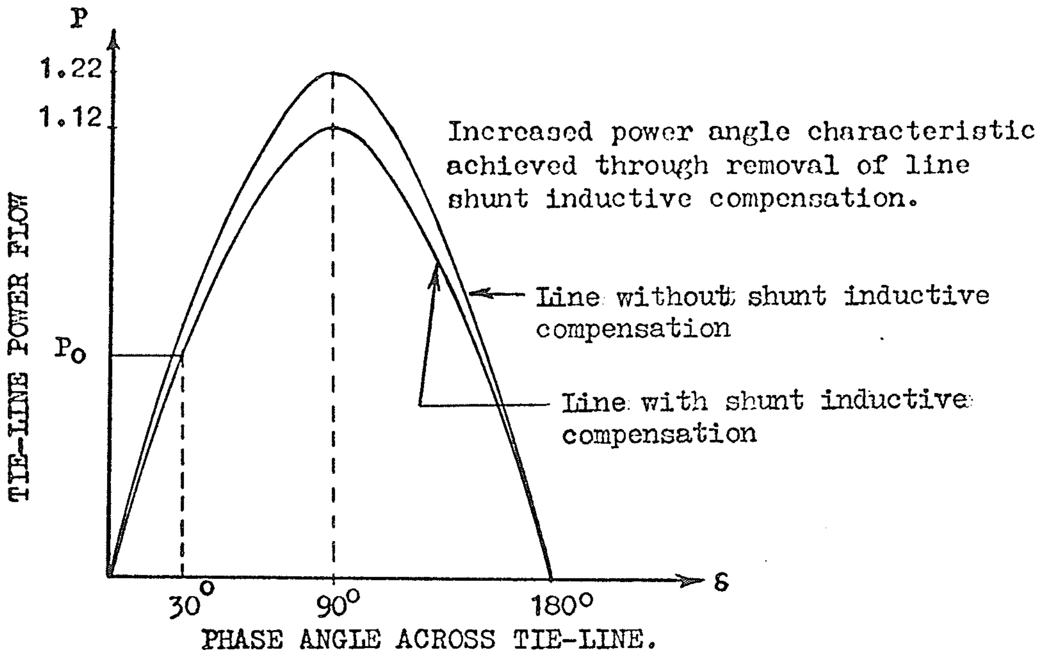


Figure 3.7 Power angle characteristic for tie-line with and without shunt inductive compensation. (No series compensation)

during upswings and vice-versa for backswings. Four cases were considered corresponding to the four cases of series switched capacitors studied in Section 3.1. The magnitude of total shunt reactance was chosen in each case to give the same degree of maximum transient swing for the same fault as the series capacitor cases as in Figure 3.2. These cases are:

Case 1. Undamped swings of machine A without tie-line control.

Case 2. Shunt switching between 0.6 p.u. capacitance and 0.178 p.u. inductance.

Case 3. Shunt switching between 0.7 p.u. capacitance and 0.189 p.u. inductance.

Case 4. Shunt switching between 0.8 p.u. capacitance and 0.2 p.u. inductance.

The swing curves for machine A for each of these shunt controllers are shown in Figure 3.8.

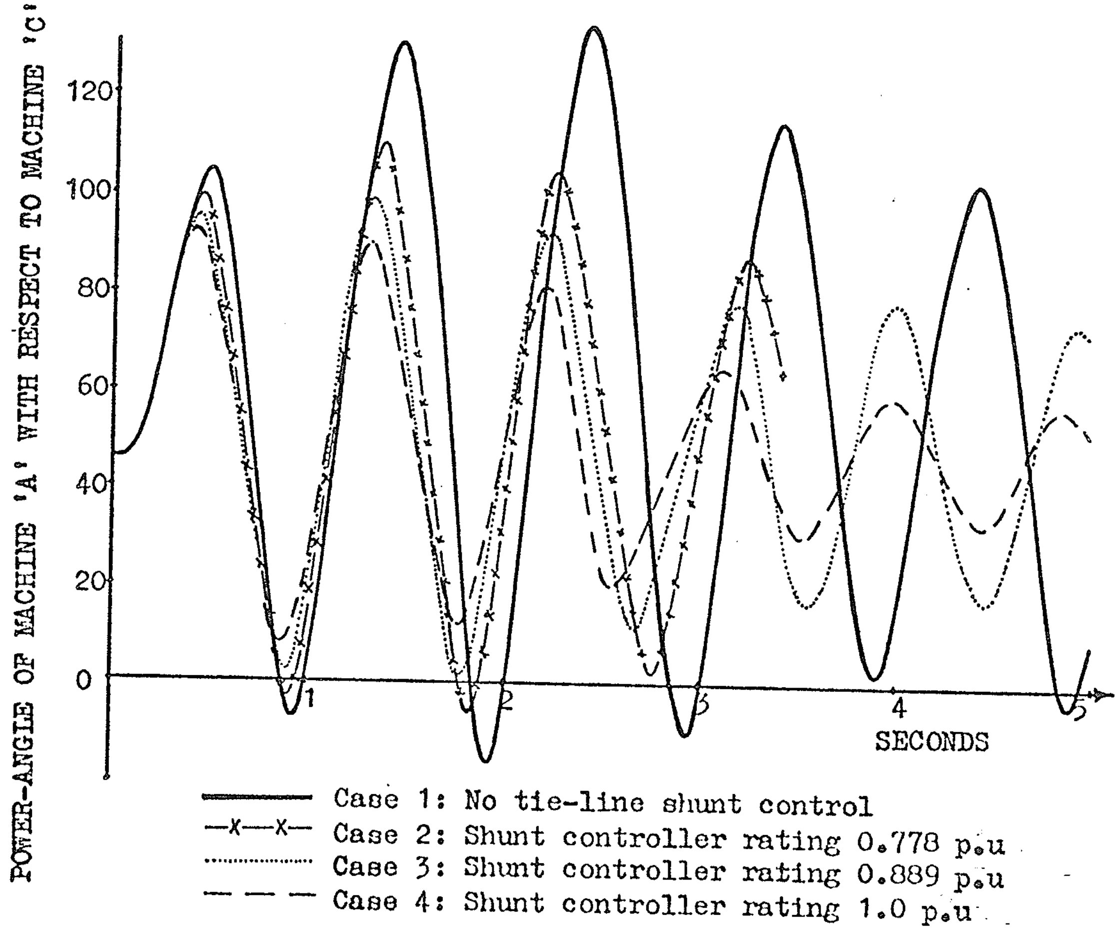


Figure 3.8 Effect of switched shunt reactance tie-line control on tie-line power angle swings.

The main conclusion to be readily observed in comparing the shunt reactance control performance with the series reactance control performance (Figure 3.2) is the additional damping obtained by shunt switching. This is a result of inductive as well as capacitive switching, whereas series control used only capacitive switching. Table 3.1 shows a comparison of maximum transient reactive power requirements between shunt and series control for these cases studied on the three machine model. Note that for all cases the steady state reactive power ratings would be less than the maximum transient ratings as determined by the short time capability of the components used.

	Short time Capacitive p.u. Rating		Inductive p.u. Rating		Switching Delay m Sec	
	Series	Shunt	Series	Shunt	Series	Shunt
Case 2	0.23	0.6	--	0.178	50	30
Case 3	0.61	0.7	--	0.188	50	30
Case 4	1.08	0.8	--	0.20	50	30

Table 3.1. Comparison of Series and Shunt Controller Ratings

The effectiveness of series control compared to shunt control is reduced by the longer switching delay assigned in this three machine model. Thus, an important consideration is the quickness of operation of switches. The operation times considered in this model are fast for conventional switches. The manufacturer of a fast high voltage circuit switch, namely S & C Electric Canada Ltd., claim in their catalogue [8] that their switch can open in eight cycles. Ideally, a switch for transient control should operate in two or three cycles; otherwise, the effectiveness of the controller is significantly reduced. To make use of reactive components for damping, the switch must be capable of fast reclosing, which, unfortunately, means an expensive circuit breaker. The S & C circuit switch is not capable of fast reclosing.

3.4 The static compensator.

An excellent way of overcoming the limitations of switching delays in tie-line controllers is to use the static compensator. The static compensator is the result of a lifetime's work by Dr. E. Friedlander who was responsible for the development of a saturable reactor which draws ac current relatively free from harmonics. [9]

The main component of the static compensator is a saturable reactor. The volt-amp characteristic of a saturable reactor is shown dotted in Figure 3.10, while the characteristic of a static compensator is shown in heavier line. The combination of capacitors and saturable reactor to form the static compensator is shown in Figure 3.9. The overall effect of the static compensator is to maintain constant voltage at its terminals. As such it is useful for:

3.4.1 Light flicker and voltage dip reduction from industrial loads.

3.4.2 Network voltage stabilization.

3.4.3 Power angle stabilization of ac tie-lines.

A comprehensive coverage of the applications of the saturable reactor and static compensator in power systems is covered by Reference [10].

The power angle characteristics for the static compensator connected to a tie-line mid-point is found as follows. Assume Thevenin voltages at each end of the transmission line remain at 1.0 p.u., and that the static compensator voltage characteristic is flat at 1.0 p.u.. Based on Equation 2.3 the power flow P through the transmission line between its mid-point and one end is found by the expression

$$P = \frac{\text{Sin } \delta/2}{X_L/2} , \qquad (3.1)$$

where $\delta/2$ = voltage power angle across the transmission line between mid-point and one end.

$X_L/2$ = series reactance of one-half line section.

However, as the power angle across the line increases,

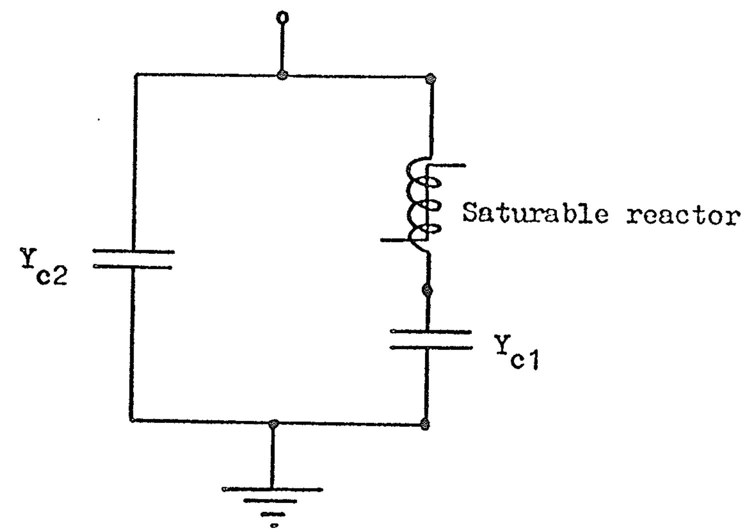


Figure 3.9 Single line diagram for shunt connected static compensator with saturable reactor.

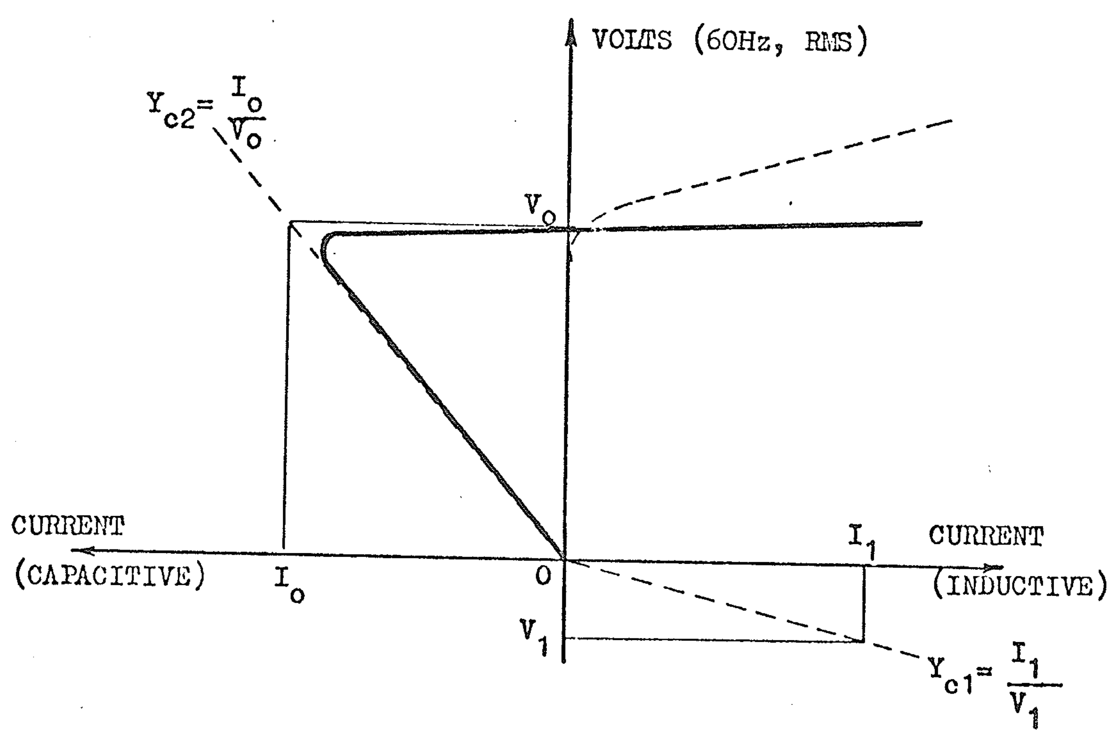


Figure 3.10 Volt-amp characteristics of static compensator

the saturated reactor becomes unsaturated, and so the static compensator is effectively a shunt capacitance Y_{C2} (See Figure 3.9 and 3.10). The power angle relationship is then

$$P = \frac{4 \text{ Sin } \delta}{X_L(4 - X_L Y_S)} \quad , \tag{2.7}$$

where $$Y_S = \frac{Y_L}{2} + Y_{C2} \tag{3.2}$$

$\frac{Y_L}{2}$ = mid-point line charging shunt admittance (when line is represented by two sections)

By equating Equations 3.1 and 2.7 it is possible to determine the power angle δ_C across the tie-line at which the static compensator discontinues its saturation characteristic, i.e.

$$\text{Cos } \delta_C/2 = \frac{4 - X_L Y_S}{4} \tag{3.3}$$

Thus, the power angle characteristic for a tie-line with static compensation can be obtained from Equations 2.7 and 3.1 and is shown in Figure 3.11.

For extra long transmission lines, one static compensator at the line mid-point may be insufficient, and two static compensators may be needed at the third points of the line, or even three at the quarter points. The equation to the constant voltage characteristic (see Figure 3.11 and assuming the static compensator

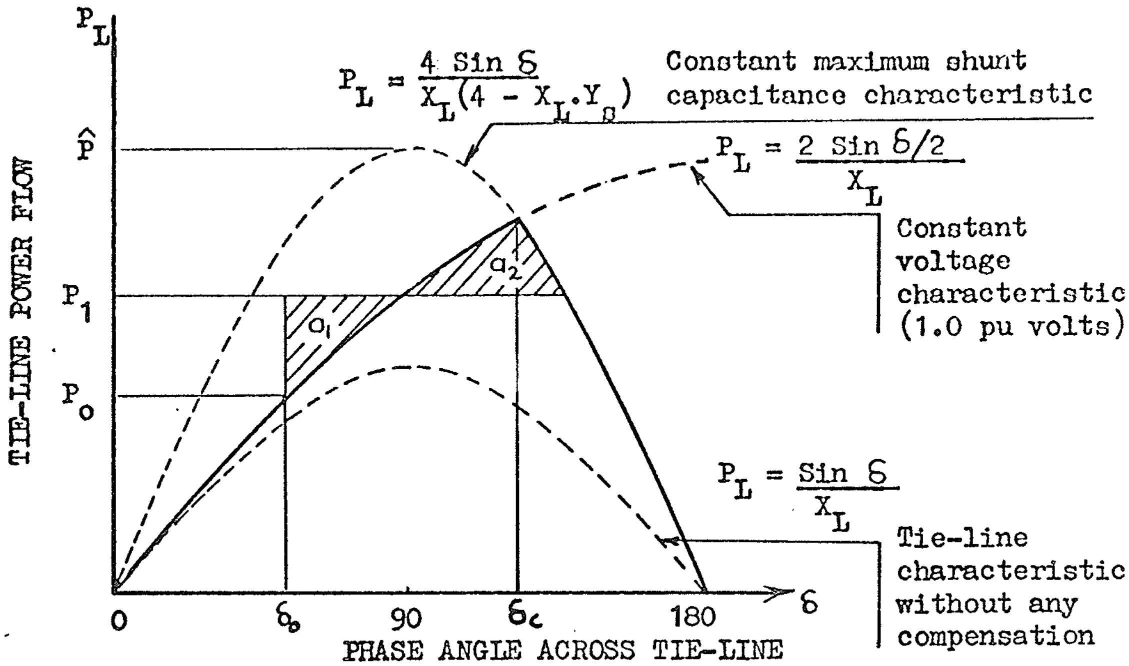


Figure 3.11 Power angle characteristic for a tie-line with a static compensator at its mid-point. P_0 = steady full load operating power. P_1 = Maximum stepped power from full load to retain transient stability.

maintains 1.0 p.u. volts at its terminals) for two equally spaced static compensators is

$$P = \frac{3 \sin \delta/3}{X_L} \tag{3.4}$$

and for three equally spaced compensators:

$$P = \frac{4 \sin \delta/4}{X_L} \tag{3.5}$$

Correspondingly, the equation for constant maximum shunt capacitance characteristic (see Figure 3.11) for two equally spaced static compensators is

$$P = \frac{27 \quad \sin \delta}{X_L(3 - X_L Y_S)(9 - X_L Y_S)} \tag{3.7}$$

and for three equally spaced compensators is

$$P = \frac{256 \quad \sin \delta}{X_L(8 - X_L Y_S)(32 - 16X_L Y_S + X_L{}^2 Y_S{}^2)} \,, \tag{3.8}$$

where δ = overall power angle between Thevenin voltage sources at each end of the line

X_L = total series line reactance in per unit

Y_S = total effective shunt admittance across the terminals of each static compensator per unit,

and it is assumed the Thevenin source voltages remain constant at 1.0 p.u. Equations 3.7 and 3.8 can be derived using A,B,C,D constants, and solving the overall matrix for constant B, which is the equivalent line impedance, enables the power angle equation (see Equation 2.3) to be formed. The effect of adding and spacing static compensators along the tie-line is to straighten the constant voltage characteristic.

3.5 Comparing series and static shunt compensation.

An example is now outlined to illustrate how a comparison between static shunt compensation and series compensation can be evaluated. The case being studied is the 500 kV line, 400 miles long, to transmit a maximum steady state power of 1000 MW (i.e. 1.0 p.u.).

Total series line reactance including Thevenin source reactances is $X_L = 0.927$ p.u., and the total distributed admittance is $Y_L = 1.0$ p.u.

Steps in evaluation are as follows:

3.5.1 Amount of series compensation. For full load power angle $\delta = 30^{\circ}$, and a series compensation efficiency K = 90%, Equation 2.1 substituted into Equation 2.3 can be written as

$$P = \frac{\sin \delta}{X_L - KX_C}$$

where $K = 0.9$

X_C = series capacitive reactance.

Solving for X_C when $P = 1.0$ and $\delta = 30^{\circ}$,

$X_C = 0.475$ p.u.

Therefore, % series compensation $= \frac{X_C}{X_L} \times 100 = 51\%$

3.5.2 Defining transient stability limits. Using the equal area criterion, the maximum step increase in power flow through the transmission line can be determined to just retain transient stability, and is found to be $P = 1.73 = P_1$ p.u. I.e. from steady state power at $P = 1.0 = P_o$ and $\delta = 30^{\circ}$, it can be found geometrically with the transmission line power angle characteristic and equal area criterion that a step increase of power to P_1 = 1.73 p.u. will cause δ to swing transiently to 120° and just remain stable. Thus, P_1 is a measure of the step change in power that a shunt compensated scheme must transiently withstand for comparison with series compensation.

3.5.3 Rating of series capacitor. The rating of the series capacitor is found in the same way as the example in Chapter 2, Section 2.2. With 51% series capacitive reactance, capable of transiently withstanding a power angle swing of $\delta = 120^{\circ}$, the maximum reactive power capability of the series capacitor can be found from the graph Figure 2.1, and is 5.6 p.u. Note that this is a transient value only, and the actual steady state de-rated value will be considerably less depending on capacitor short time overload capability.

3.5.4 Shunt static compensator power angle characteristic. For the static compensator at line mid-point, the constant voltage power angle characteristic from Equation 3.1 can be drawn. The maximum step change in power to P_1 = 1.73 p.u. for transient stability limits is used to determine the magnitude of the maximum shunt capacitance power angle characteristic by the equal area criterion. See Figure 3.11 where shaded area

$a_1 = a_2$. For this example with compensator at line mid-point, area a_2 could not be made equal to a_1 without having nearly infinite shunt capacitance. So two shunt static compensators distributed equally along the line are necessary, and the corresponding constant voltage power angle characteristic from Equation 3.4 is used. Now a sine wave of acceptable magnitude to allow areas $a_1 = a_2$ can be constructed for the constant maximum shunt capacitance characteristic.

3.5.5 Rating of shunt capacitance. The rating of the shunt capacitance for a static compensator (Y_{C2} in Figure 3.9) can be determined from the peak magnitude $\hat{P}$ of the constant maximum shunt capacitance power angle characteristic found above. Equation 3.7 defines this characteristic for two equally spaced static compensators. The shunt capacitive reactance can be determined if Equation 3.7 is solved for Y_S, where Y_S equals the total equivalent capacitance across the terminals of each saturable reactor. Solution for Y_S is facilitated by the graphs in Figure 3.12 where the product $Y_S X_L$ is plotted against $\hat{P}X_L$ for one, two and three equally spaced shunt capacitances. For this example, $\hat{P} = 3.46$, and so the product $\hat{P}X_L$ = 3.46 x 0.927 = 3.21. Reading directly from the

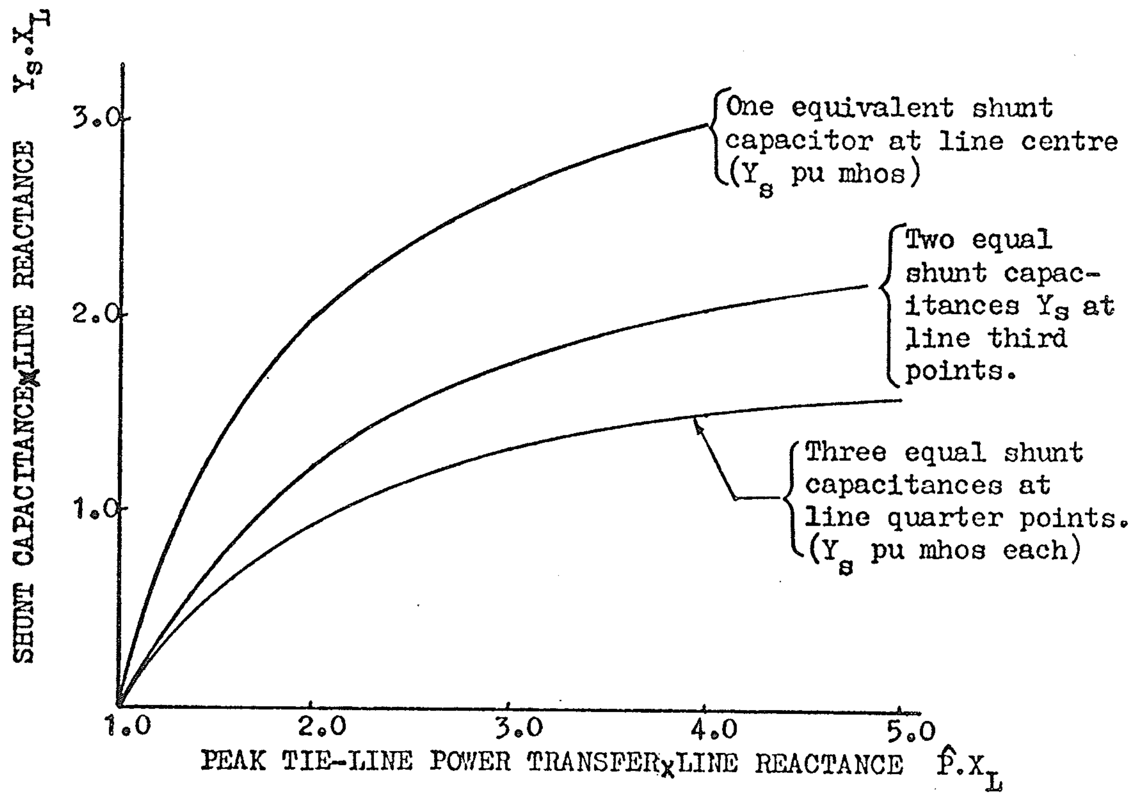


Figure 3.12 Graph to determine relationship between peak tie-line power transfer and equivalent shunt capacitances at various line positions to maintain 1.0 pu volts at those positions.

graph in Figure 3.12, the product $Y_S X_L$ can be found from the characteristic for two equally spaced identical shunt capacitances along the line. Thus, $Y_S X_L = 1.82$, hence $Y_S = \frac{1.82}{0.927} =$ 1.96 per unit (mho). The equivalent circuit for this arrangement is shown in Figure 3.13. The transmission line charging capacitance is represented by three π sections so that the

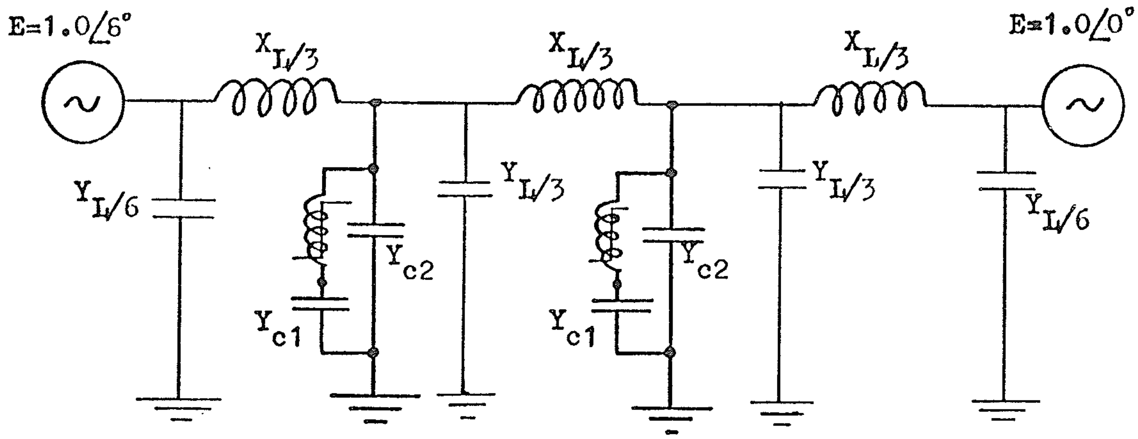


Figure 3.13 Tie-line equivalent circuit with two shunt static compensators at the line third points.

effective charging capacitive admittance at each static compensator is $\frac{Y_L}{3}$ per unit. Consequently, the total effective capacitance at each static compensator is $Y_S = \frac{Y_L}{3} + Y_{C2}$ where Y_{C2} is the admittance of the maximum shunt capacitance which must be added to achieve the stability level desired. Thus,

$$Y_{C2} = Y_S - \frac{Y_L}{3}$$

$$= 1.96 - 0.33$$

Therefore, $Y_{C2} = 1.63$ per unit.

Since the nominal voltage of the transmission line is 1.0 p.u., then the rating of this shunt admittance is Y_{C2} p.u. Thus, the maximum capacitive requirement for shunt static compensation is $2Y_{C2} = 3.26$ p.u. reactive power. This value of capacitive reactive power can now be compared with the maximum series capacitive reactive power requirement which was found to be 5.6 p.u. in Section 3.5.3.

3.5.6 Saturable reactor rating. The saturable reactor must be capable of absorbing all the excess capacitive MVAR on the transmission line at no-load. To reduce the size of the saturable reactor, the shunt capacitance required on large transient swings can be switched in and removed as required by a fast operating switch or circuit breaker. The size of each saturable reactor to satisfy normal compensation requirements can be found using the theory developed in this section, or from conventional calculations. For this example, the capacity of each saturable reactor for steady state compensation must be 0.33 p.u. (MVAR) or approximately $\frac{Y_L}{3}$ p.u. (MVAR) inductive.

Summarizing the comparison between series and static compensation for this example using per unit quantities on 1000 MW base:

	Series	Static
Peak transient capacitive MVAR requirement	5.6	3.26
Normal shunt inductive compensation	0.8	0.33
Saturable reactor capacity	---	0.66

In addition, fast acting switches or circuit breakers would be required for the static scheme so that shunt capacitance could be transiently switched in for large power angle swings across the transmission line.

The purpose of this example is to illustrate how static shunt compensation for a long tie-line can be determined and to show that its MVAR requirement can be comparable to or less than that required for series compensation. Cost of the saturable reactor may be prohibitively high for an economical alternative to series compensation.

3.6 Dynamic performance of static compensation.

A static compensator was modeled into the three machine power system model (see Appendix I) and positioned and scaled to give the same degree of transient stability as was achieved with some cases of series capacitors in the study reported in Section 3.1 and Figure 3.2. (Compare also with switched shunt reactance as studied in Section 3.3 and Figure 3.8.) The three cases studied for comparison are:

Case 1. Undamped swings of machine A without tie-line control.

Case 2. Shunt capacitance = 0.4 p.u., and maximum transient utilized capacity of saturable reactor = 0.7 p.u.

Case 3. Shunt capacitance = 0.6 p.u., and maximum transient utilized capacity of saturable reactor = 0.85 p.u.

The swing curves for machine A for each of the above three cases are shown in Figure 3.14.

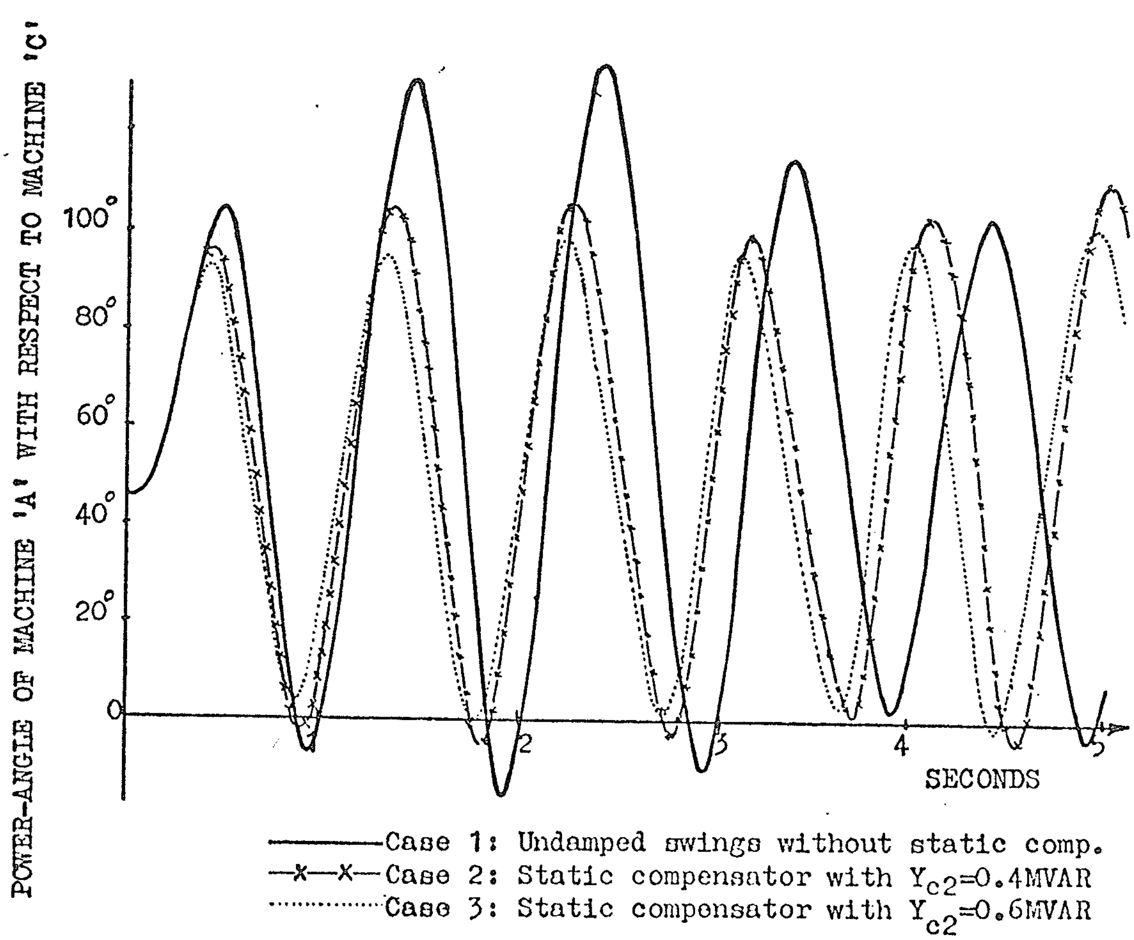


Figure 3.14 Effect of static compensator on tie-line swing curves.

The important observations from this study are firstly, improvement in dynamic stability is achieved with static compensation, and secondly, although transient stability is improved, the static compensator does not contribute to damping. It may be possible, however, to incorporate damping in the saturable reactor by means of a dc winding to control the saturation level. If damping with the static compensator can be achieved, then less shunt capacitance would be needed because the resulting increased damping would allow the constant maximum shunt capacitance characteristic (see Figure 3.11) to be reduced with the transient stability still preserved.

3.7 A variable reactor.

The saturable reactor is a continuously variable reactor which maintains controlled ac terminal volts. Another variable reactor capable of acting in both capacitive and inductive modes is described in this section. Its principle of operation is to shunt connect the h.v. primary winding of a transformer having a large high voltage to low voltage turns ratio so that the secondary is capable of passing heavy current at low voltage. By means of low voltage heavy current fast-acting switches, capacitors and/or air cored reactors are switched into the transformer secondary circuit as desired. The secondary reactance is reflected through the transformer to the high voltage primary, thus acting as a direct shunt reactance

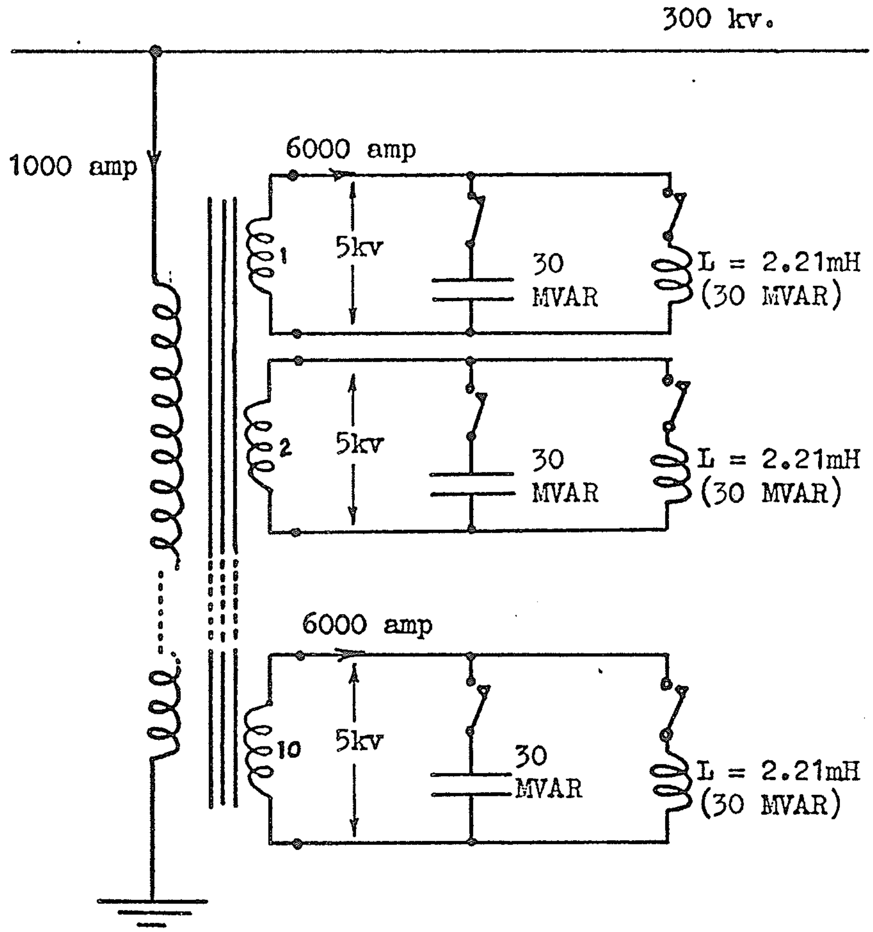
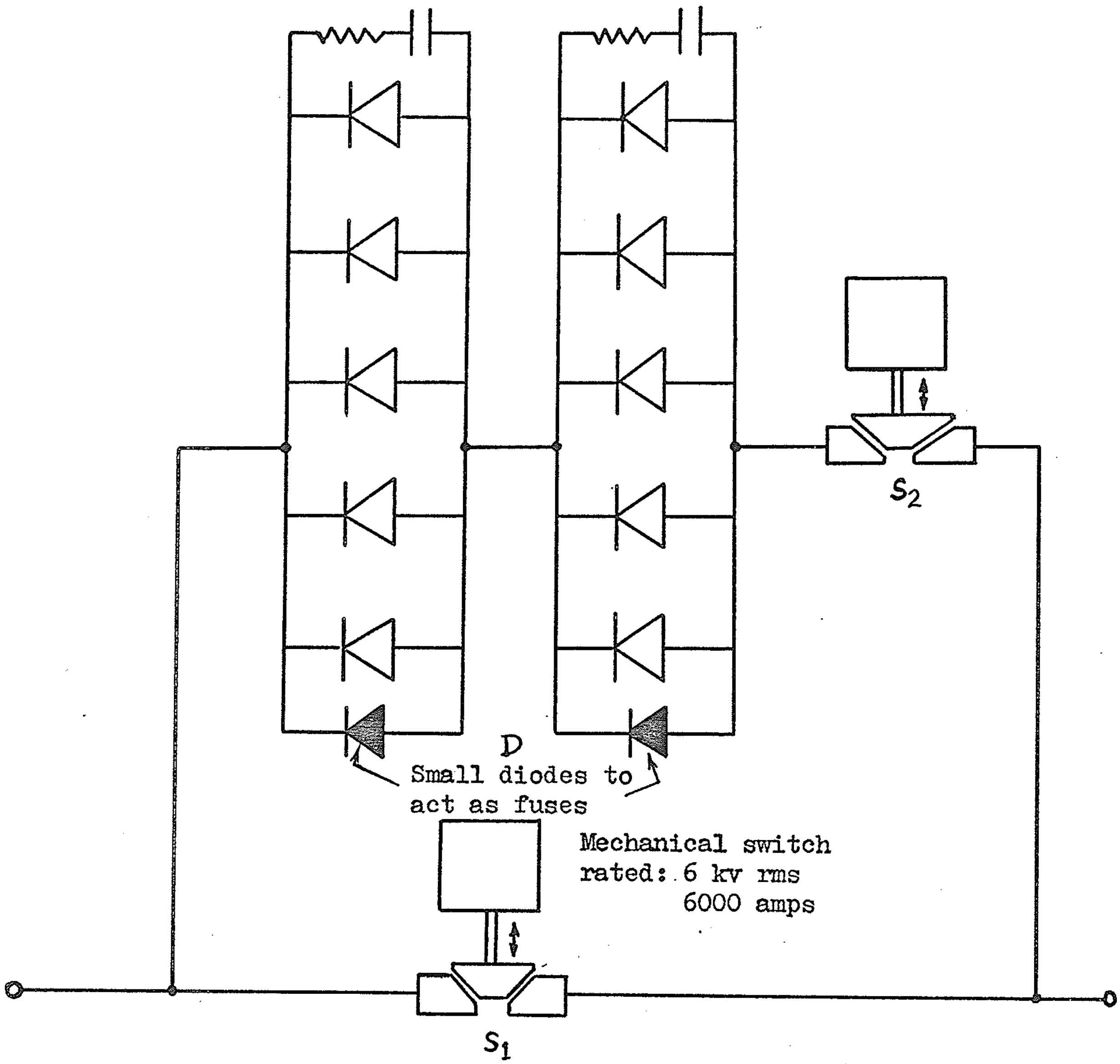


Figure 3.15 Circuit diagram of single phase 300 MVAR 20 step variable reactor having ten secondary low voltage circuits.

to the transmission line. See the diagram of Figure 3.15 where one phase of a 500 kV line is shown shunted with a 300 MVAR variable reactor. Although the idea for this reactor is theoretical, its feasibility should be examined. Consider the following factors:

3.7.1 A low voltage, heavy ac switch. The main problem with a heavy current switch in an inductive circuit is arcing. A non-arcing heavy ac switching operation can be achieved with a diode and two fast-acting switches. By connection as shown in Figure 3.16, circuit breaking is possible by opening switch S_1 when diodes D can forward conduct so that the current is diverted through the diodes. For the half cycle when there is reverse bias on the diodes, no current flows through the circuit, and so switch S_2 can be opened without arcing. A similar procedure follows for closing the switch to remake the circuit. Such a switch would need development and, in particular, the mechanical ability to make and open contacts within the half cycle. Because of the low voltage operation, for example 5 kV, the cost of the switch should be minimized, the major cost being in the diodes.

3.7.2 Air cored reactors. Calculations indicate that secondary connected air cored reactors would be of an acceptable size for installation close to the transformer. A 5 kV, 6000 amp, 60 hertz aluminum air cored reactor would be approximately one cubic metre in total volume. Furthermore, calculations indicate the Q value (that is, ratio of reactance to resistance) of



Large diodes: 5 kv PIV, 900 amp continuous.
Small diodes: 4.5 kv PIV, to act as fuses.
Mechanical switches controlled to operate during half cycle when current is not flowing or can be diverted.
Diode protection available through mechanical switches and small diodes.

Figure 3.16 Design of fast acting low voltage high current switch for 5 kv, 6000 amps ac operation.

the secondary circuit with aluminum conductors would be large enough to allow secondary circuit losses to be acceptable. Additional reactors and switches in the secondary circuits would enable the transformer to overload, and, consequently, a higher short time rating of the variable reactor would be possible for increased damping ability.

3.7.3 Capacitors. Capacitors in the secondary circuit would occupy the largest volume per kVA of all the equipment in the variable reactor. The amount of steady state shunt capacitance for normal shunt compensation could be determined similarly to the example in Chapter 2, Section 2.5.

3.8 The variable reactor for shunt control and compensation.

The controlled variable reactor shunt compensator would operate similarly to the saturable reactor shunt compensator as a tie-line controller. To illustrate this, consider the same transmission line example used in Section 3.5 to evaluate the rating of reactive elements for series and static compensation. Assume that the variable reactor compensator is capable of controlling its terminal voltage at 1.0 p.u. under steady state transmission conditions. During a large transient power angle swing, shunt inductance is removed and shunt capacitance added to increase the terminal volts to a controlled maximum of, say, 1.15 p.u. during the upswing. This increased terminal volts of the shunt controller on the transmission line would give a greater power transfer capability than if the terminal volts remained at 1.0 p.u. The transient power angle characteristic for the variable reactor controller at the tie-line mid-point is shown in Figure 3.17.

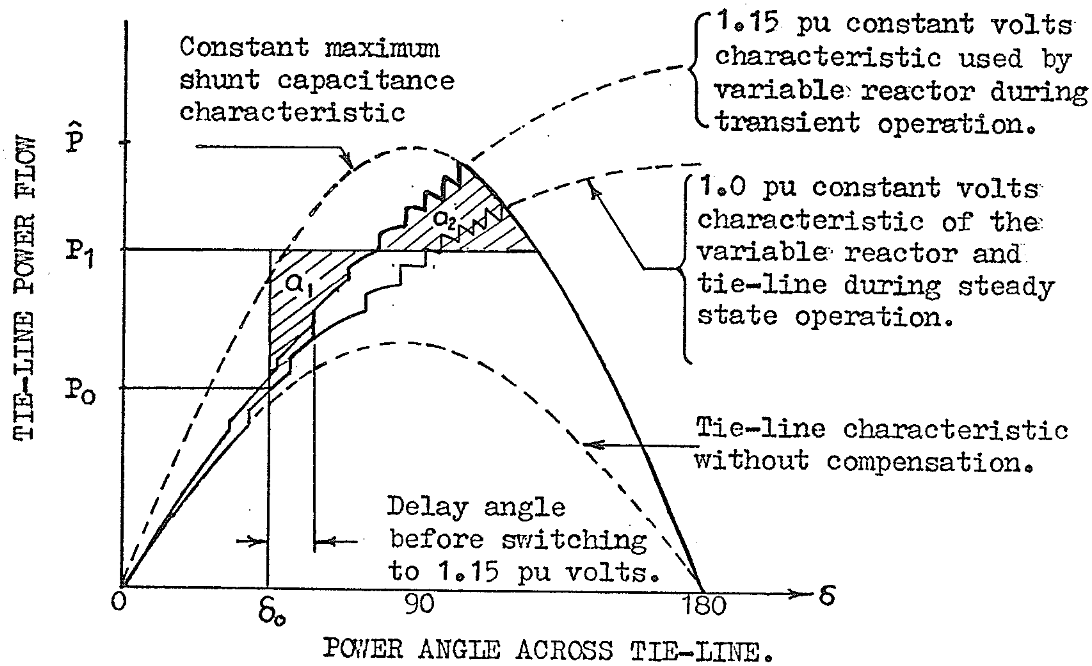


Figure 3.17 Power angle characteristic for a tie-line with a variable reactor controller at its mid-point capable of transiently maintaining 1.15 pu volts at the line mid-point.

It is known that the tie-line must transiently withstand a step change in power transfer from $P_o = 1.0$ p.u. to $P_1 = 1.73$ p.u. (See Section 3.5.2.) As can be seen from the power angle characteristic in Figure 3.17, transient operation close to the 1.15 p.u. constant voltage characteristic allows the constant maximum shunt capacitance characteristic to be determined by the equal area criterion. Note that in Section 3.5.5 it was found that the static compensator at line mid-point was inadequate because the equal area criterion could not be realistically met. But, because increasing the transient performance of the controller to follow near the 1.15 p.u. constant voltage characteristic during the transient upswing, the constant maximum shunt capacitance characteristic can be determined with a reasonable peak magnitude of $\hat{P} = 2.5$ p.u. power. Therefore, $\hat{P}X_L = 2.5 \times 0.927 = 2.32$. Reading directly from the curves in Figure 3.12, the total maximum shunt admittance Y_S at the line mid-point can be determined as 2.45 p.u. based on 1.0 p.u. volts. The equivalent line charging admittance at the centre of the line is assumed to be $Y_L/2$ p.u. Then, from Equation 2.4, the additional shunt admittance Y_C required from the variable reactor controller is

$$Y_C = Y_S - \frac{Y_L}{2}$$

Therefore, $Y_C = 1.95$ p.u. capacitive

If the mid-point volts $V_B = 1.15$ p.u. during transient conditions, then the peak transient capacitive reactive power requirement for the variable reactor controller is $V_B{}^2 Y_C$ which is 2.58 p.u.

The transformer rating must transiently accommodate the 2.58 p.u. capacitive reactive power requirement. Also, the variable reactor must be capable of absorbing all excess capacitive MVAR at the line centre at no load. Therefore, the air cored reactors must be rated at $Y_L/2$ p.u. inductance which for this example is 0.5 p.u. The reactive requirements of the variable reactor for this transmission line example using per unit quantities based on 1000 MW base are as follows:

Peak transient capacitive requirement:	2.58
Normal shunt inductive compensation: (situated at the line ends)	0.4
Air cored reactor capacity:	0.5
Transformer steady state capacity (approximately):	0.7

When compared with the series compensated scheme for the transmission line as tabled in Section 3.5 of this chapter, it can be seen that the peak transient capacitive MVAR requirement for the variable reactor controller is less than one-half of that required by series compensation for comparable transient stability. It is anticipated that this significant saving in capacitors would place a variable reactor scheme in a competitive position compared with series compensation. Note that this example is an illustration, and for exact design, equations of the transmission line with distributed parameters in the form of A,B,C,D constants should be used. However, the basic design technique and form of design graphs used in this chapter outline a suitable design procedure.

The transient and dynamic performance of a variable reactor shunt controller modeled on the three machine model (Appendix I) is the same as the switched shunt reactance controller considered in Section 3.3 and Figure 3.8.

3.9 Transient rating of capacitors.

The example comparing series and shunt compensators for transient tie-line control outlined in this chapter (Sections 3.5 and 3.8) developed values of peak transient capacitive MVAR requirements. Capacitors, like other electrical devices, have a transient withstand rating which can be much higher than normal steady state ratings. The short time overload capability of capacitors would depend upon their manufacture and design. Bloomquist and Wilson in Reference [16] referring to NEMA standard 48-135 suggest that the total transient and steady state currents through capacitors should not exceed 1.5 times rated. Consequently, if this standard is at least adhered to by the manufacturers, then a simple rule of thumb for maximum transient capability of capacitors is 2.25 times steady state rating.

Limiting the transient rating of capacitors reduces the transient capability of series compensation much more than shunt compensation and control. To illustrate this fact, consider a series compensated transmission line where full load steady state rating of capacitors is reached when the line is loaded to 30° power angle. From Equation 2.2, the capacitor MVAR rating is directly proportional to $\sin^2 \delta/2$, where δ is the power angle. By simple arithmetic, the maximum transient power angle swing to overload the capacitor 2.25 times its normal rating is 45.5°. If the capacitor protection operates when the power angle swings exceed 45.5°, then a drastic reduction in transient stability will result. Shunt capacitance on the other hand, is not subject to such great overloads on transient swings because the line voltage tends to reduce with increased power angle or fault current.

It is recommended, therefore, that transient withstand capability of capacitors be included in economically evaluating the series and shunt compensation and control alternatives for a transmission line.

3.10 Positioning of tie-line shunt controllers.

The position of a tie-line shunt reactive controller along the tie-line can affect the system transient stability. To evaluate the contribution of a shunt controller to system transient stability, a performance index 'T' is defined as follows.

Firstly, for the uncontrolled tie-line and power system subject to a severe temporary fault of duration Δt_o, observe the peak angle $\hat{D}$ across the tie-line of the first transient swing. Then, secondly, for the controlled tie-line observe the temporary fault duration Δt_1 required to produce the same peak angle $\hat{D}$ for its first transient swing. The performance index T is then defined as

$$T = \frac{\Delta t_1}{\Delta t_o} \qquad (3.9)$$

A variable reactor shunt controller was placed in the tie-line to machine A in the three machine model (Appendix I). The performance index was measured for the shunt controller placed in various positions along the tie-line and the results are shown in Figure 3.18 where T is plotted against tie-line length in p.u. reactance.

For best transient stability, the shunt controller should be placed at the equivalent centre of the tie-line, or at least within ±15% of the line length from the equivalent centre.

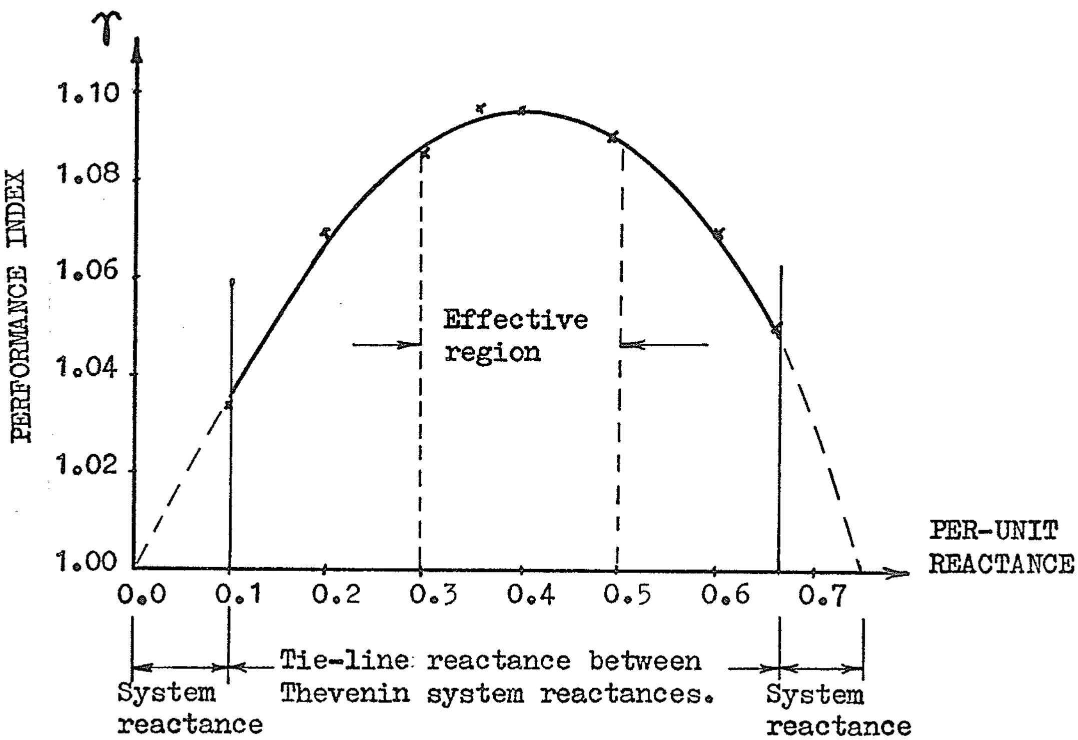


Figure 3.18 Effectiveness of shunt controllers with positioning along the tie-line.

3.11 <u>Short circuit limiting coupling</u>.

It is worth mentioning briefly the application of saturable reactors for limiting the short circuit capacity between two busbars. A saturable reactor is paralleled with a capacitor and placed as a series element in a tie-line between two busbars. Under normal transmission conditions, current flow along the interconnection passes through the capacitor, by-passing the saturable reactor which is unsaturated. With a fault on either end of the interconnection, the voltage across the capacitor increases with fault current, and the saturable reactor saturates, while its inductance reduces. A parallel L - C circuit element is formed with impedance increasing as the saturable reactor inductance reduces, thus limiting the fault current through the interconnection. The short circuit limiting coupling not only limits fault power transfer, but operates instantaneously to isolate a fault from the healthy portion of the power system. [10]

3.12 Optimization and Reliability.

To optimize the rating of a series or shunt reactive power controller or compensator, decisions must be made on the following points.

3.12.1 The position along the transmission line at which the reactive power device for control or compensation will be the most effective and whether it can be installed there.

3.12.2 The transient stability limit, maximum power angle and fault load for which the compensator or controller should be capable of staying in operation through.

3.12.3 The short time reactive power overload which the reactive devices can tolerate.

3.12.4 The maximum overvoltage allowed for the transmission line.

3.12.5 The transmission line parameters.

Knowing answers to each of these five points will enable a design to be determined for both a compensator or a control device.

A further point to be considered in the design is the reliability of the reactive power device. This factor will determine the unit size and the number of units to be installed. A decision has to be made on how much power transfer capability can remain on the transmission line with loss of one unit. It is expected that compensating or controlling devices without moving parts will be more reliable than those controllers with moving parts and electronic control systems. A complete study of optimization and reliability is not included in this dissertation.

3.13 Summary of chapter.

Series and shunt tie-line reactive power controllers have been compared in this chapter. Shunt controllers can be designed to have similar transient stability limits to series compensated tie-lines. The main advantage of shunt control is the relative immunity from transmission line faults and disturbances. The methods of shunt reactive power control are:

3.13.1 Switching shunt reactors and capacitors.

3.13.2 Using the saturable reactor as a static compensator.

3.13.3 Possible use of the variable reactor controller.

The proposed variable reactor controller is considered a feasible alternative in the tie-line control problem, that is, providing a fast operating and reliable low-voltage heavy current switch can be developed.

CHAPTER 4

REAL POWER TIE-LINE CONTROLLERS

4.0 Real power controllers defined.

A real power tie-line controller absorbs or injects real power into the ac system, whereas, reactive power controllers only affect real power flow by changing reactive elements in the network. In Chapter 1, Section 1.2, it was shown using a linear power system model that real power added to the ac system could significantly improve tie-line transient stability if suitably controlled to provide damping. The methods of supplying real power to the ac system that are studied in this chapter are:

4.0.1 Synchronous condensor and excitation control.

4.0.2 Inertia generators.

4.0.3 D.C. link.

Other methods such as braking resistors and fast valving are obvious and not considered herein.

Another important difference between the real power controller and the shunt reactive power controller for improvement of tie-line stability is positioning. The shunt reactive power controller is best positioned at the line centre, and the real power controller at the end of the tie-line in the power system of least total effective installed generation capacity so that its damping and inertia contribution can be significant.

4.1 The synchronous condensor.

The synchronous condensor is a reactive power controller in steady state operation acting as a shunt compensator. However, with a fault or disturbance causing tie-line power angle swings, real power may be supplied to or taken from the power system as the synchronous condensor transiently operates in the generating or motoring modes. Transient stability in a power system with synchronous condensors is improved through, firstly, the rotor inertia conveniently absorbing or supplying energy during transient conditions, and, secondly, the amortisseur windings increasing system damping. Thus, the transient stability across a tie-line is improved if a synchronous condensor is attached to it or electrically near it. The steady state stability is improved because of its shunt compensation action or voltage support.

The effect of a synchronous condensor was studied when connected half way along the tie-line to machine A in the three machine power system model (appendix I). The synchronous condensor was represented in detail based on Park's equations (see p. 73 of Reference [11]) so that the only damping in the power system model was entirely due to the synchronous condensor. The synchronous condensor rating was approximately one-half of the tie-line rating, and its inertia one-quarter of machine A. An improvement in transient and dynamic stability was observed, and some damping of the total power system resulted. Further improvement in transient stability and damping was observed when the synchronous condensor inertia was increased. The effect of excitation stabilizing was also studied by attaching a fast-acting exciter to the synchronous condensor field winding and deriving a control signal from the tie-line frequency. The effectiveness of excitation stabilizing is a function of the sine of the machine power angle which is zero for a synchronous condensor operating at steady state. Consequently, excitation stabilizing of such is not normally practiced. However, transient stability across a tie-line can be significantly increased if, on sensing a transient power angle swing across the tie-line, the excitation voltage of an attached synchronous condensor is forced to its ceiling limit. This in turn will raise the "internal emf" of the machine and tend to raise its terminal volts, thus improving the transmission line power transfer capability. This effect was indeed observed on the model being studied. During post-first swing conditions the excitation stabilizing failed to have any further effect and so is only useful in reducing transient stability.

Four cases were studied on the three machine model:

Case 1. Undamped swings of machine A without synchronous condensor attached.

Case 2. Effect of synchronous condensor without excitation stabilizing and with inertia constant H = 0.65 MWsec/MVAR.

Case 3. Effect of same synchronous condensor without excitation stabilizing and with inertia constant increased to H = 1.5 MWsec/MVAR.

Case 4. Effect of synchronous condensor with excitation stabilizing and with inertia constant H = 0.65 MWsec/MVAR.

The swing curves for machine A for each of these four cases are shown in Figure 4.1.

The main conclusions from this study of synchronous condensors as tie-line controllers are:

4.1.1 The inertia and amortisseur windings of the synchronous condensor improve transient stability and damping, thus possibly justifying maximizing these parameters.

4.1.2 Excitation stabilizing can be used on synchronous condensors to improve tie-line transient stability.

4.2 Inertia generators.

The concept of using a synchronous condensor to help stabilize a power system leads to the possibility of using the rotating inertia of machines to absorb and release damping power to the ac system. The main

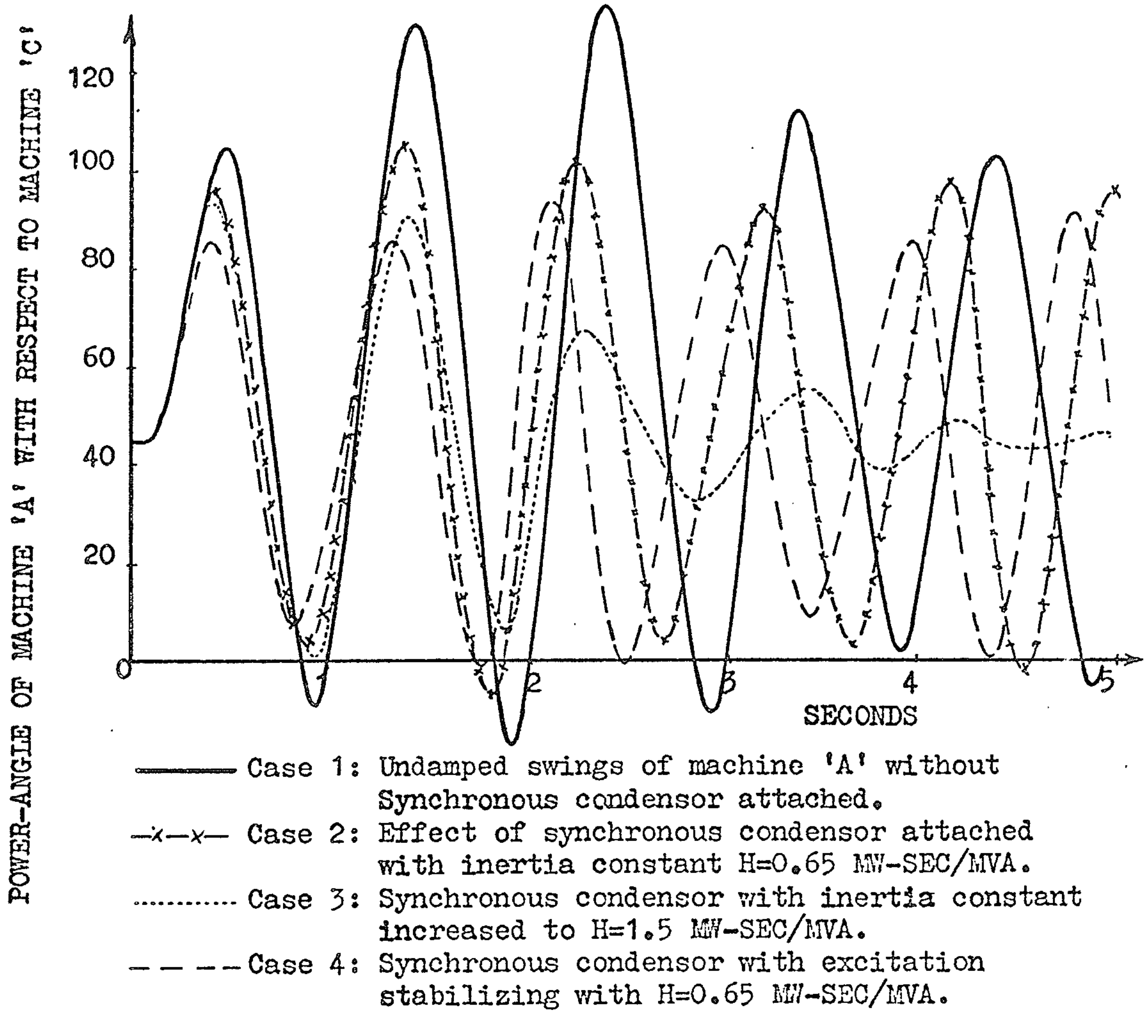


Figure 4.1 Effect of synchronous condensor on tie-line transient stability.

disadvantage of the synchronous condensor beside cost is loss of synchronism from too violent a transient disturbance. One method of overcoming this is to provide the synchronous condensor rotor with a divided winding field which with controlled excitation on each field winding allows a resultant field vector to be formed to rotate relative to the rotor. With the field vector less dependent on the rotor, it is possible to make optimum use of the rotor inertia to deliver or absorb real power from the power system as desired. Rotor inertia can be increased with a flywheel.

The concept of the divided winding rotor is not restricted to synchronous condensors, but to generators as well. (See Reference [12].) However, it may not be essential to have a divided winding rotor in a generator unless transient stability is so poor that it can be justified. Fast excitation stabilizing on generators is perhaps the easiest and cheapest method of damping one end of a tie-line to improve its transient stability performance.

4.2.1 An extension from the divided winding rotor to produce a rotating field vector is to use a conventional three phase rotor winding as per the induction motor. If the rotor windings are excited with very low frequency three phase supply, then the desired rotating field vector with respect to the rotor is achieved. The controlled three phase low frequency supply for the rotor can be produced from a cyclo-convertor. By suitably controlling the frequency of the cyclo-convertor, it is possible to deliver or absorb real power between the ac system and the rotor inertia. Note that rotor inertia can be increased by a flywheel for greater effectiveness. [13]

4.2.2 A further extension of the induction machine application is to provide pole changing facility for the stator with fast-acting switches. The accelerating or decelerating power to the induction motor rotor as a result of pole switching can be used to provide instantaneous power for damping. [14]

4.2.3 Perhaps the most controllable method utilizing machine inertia to store or release energy is to connect the ac machine with flywheel to the ac system through a dc link. The advantages of the dc link are fast controllability and its asynchronous isolation of the machine from the power system. Consequently, large speed changes of the ac machine rotor would be tolerable during transient conditions. Another use of the dc link inertia generator is to absorb or supply large power surges from pulsed power loads when the ac system cannot effectively handle such surges. [15]

4.3 DC link.

Of all the tie-line controllers, the use of hvdc transmission for interconnections is the most effective in improving power system stability. The main advantages of hvdc transmission are well known, but the advantages relating to tie-line control are:

4.3.1 Fast control and regulation of transmitted power.

4.3.2 The dc link is asynchronous in nature, allowing the ac systems at each end to be frequency independent.

4.3.3 The dc intertie does not add to the short circuit capacity of the ac system.

4.3.4 The dc tie-line can be constructed in stages with load growth.

4.3.5 Considerable damping is possible in the ac systems at each end of the dc link.

In order to investigate the effectiveness of the dc link as an inertia generator in stabilizing ac tie-lines, the twelve machine ac power system model of Saskatchewan-Manitoba-U.S.A. (See Figure 3.3) was studied with ac system damping controls on the dc link. The dc link model is shown in Figure 4.2, and the control constants were determined very easily from a few trial and error runs of the DENA program (Appendix II). These control constants are possibly not optimum for the power system configuration and load flow condition of the power system model, but it is doubtful that optimum ac system damping controls exist for a dc link when there are continuing changes in the ac system. Power system damping by dc link is still an area to be satisfactorily explored.

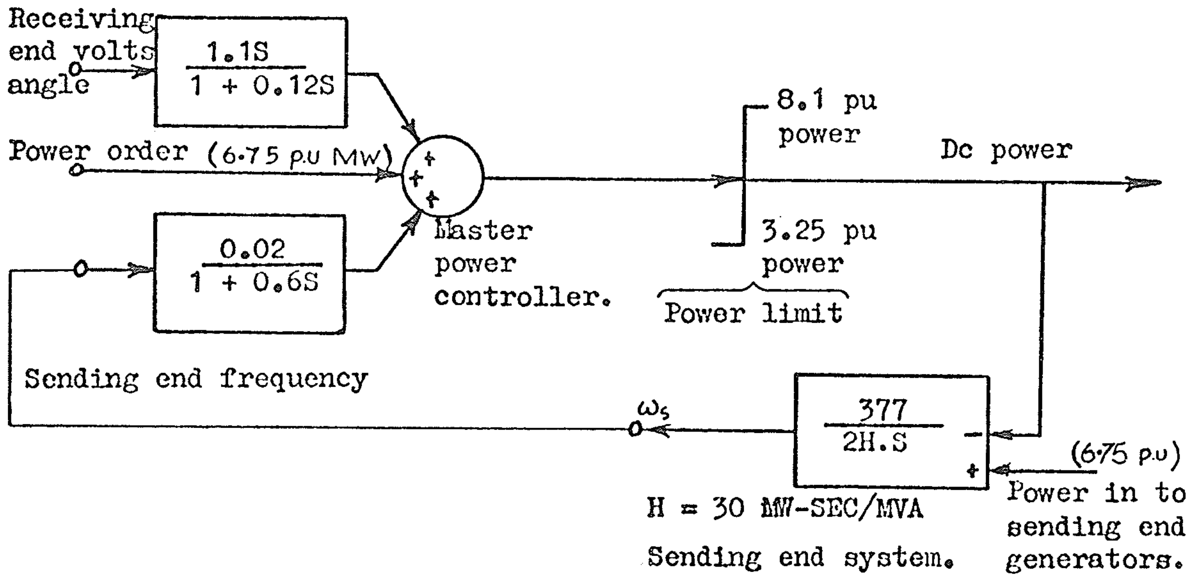


Figure 4.2 Simple dc link representation for DENA program.

Two fault situations were studied, and the swing curves of various machines throughout the twelve machine model were examined. These fault situations were:

Fault 1. A 0.5 second temporary block of one dc link pole of 225 MW at Winnipeg, Manitoba.

Fault 2. A permanent loss of 200 MW of load at Regina, Saskatchewan.

The swing curves for the Regina machine, the Winnipeg River machine and the power angle across the Manitoba-U.S.A. tie-line are shown for Fault 1 in Figure 4.4 and for Fault 2 in Figure 4.3.

The cases studied for each fault are as follows:

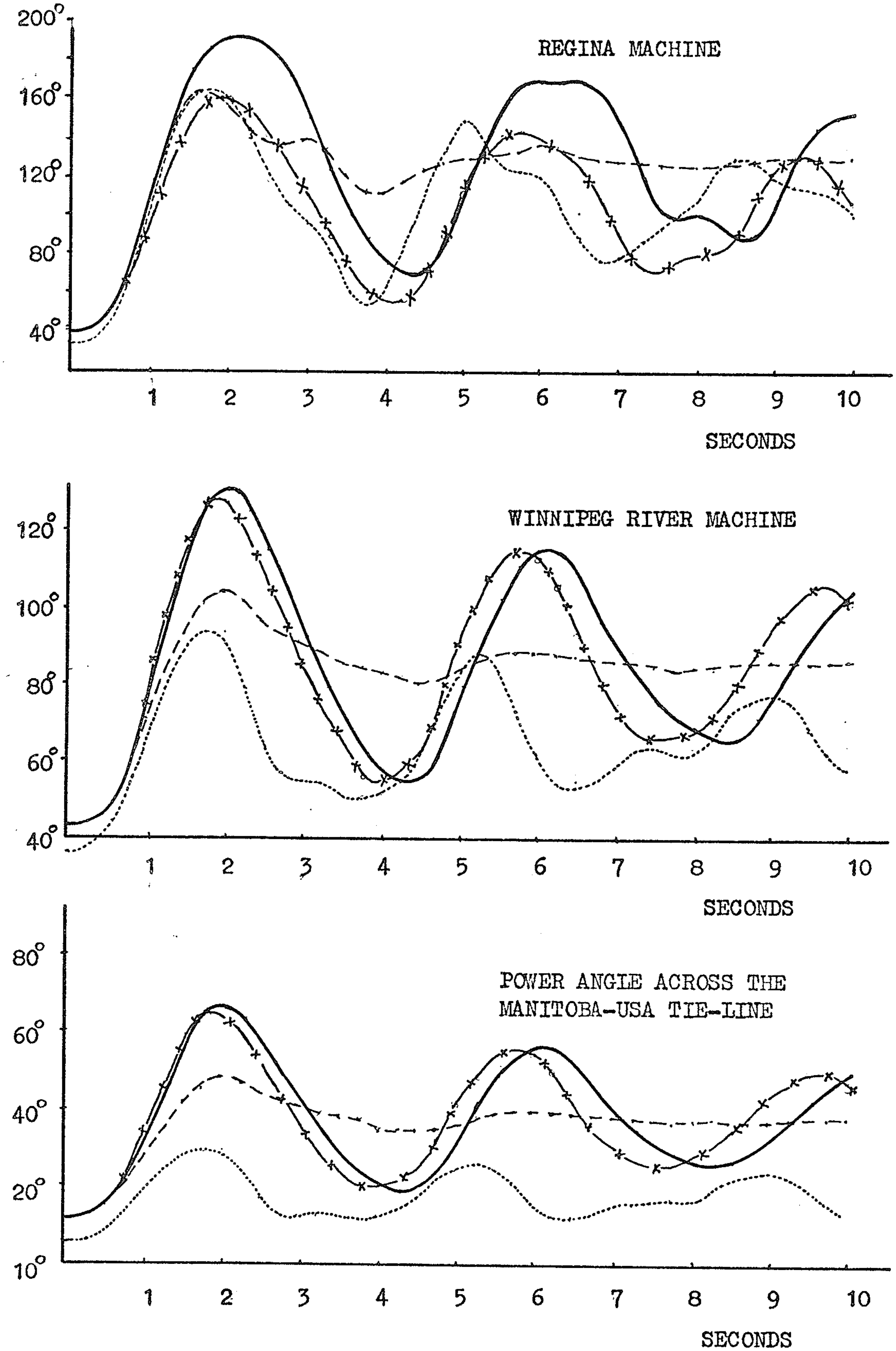


Figure 4.3 Swing curves of U.S.A-Manitoba-Saskatchewan power system model with the permanent loss of 200 MW of load at Regina. Cases are: 1 —— no dc link ac system damping, 2 ·········· no dc damping but with two parallel Manitoba-U.S.A tie-lines, 3 ×—×—× no dc damping but with two parallel Manitoba-Saskatchewan tie-lines, 4 ---- dc link ac system damping in use.

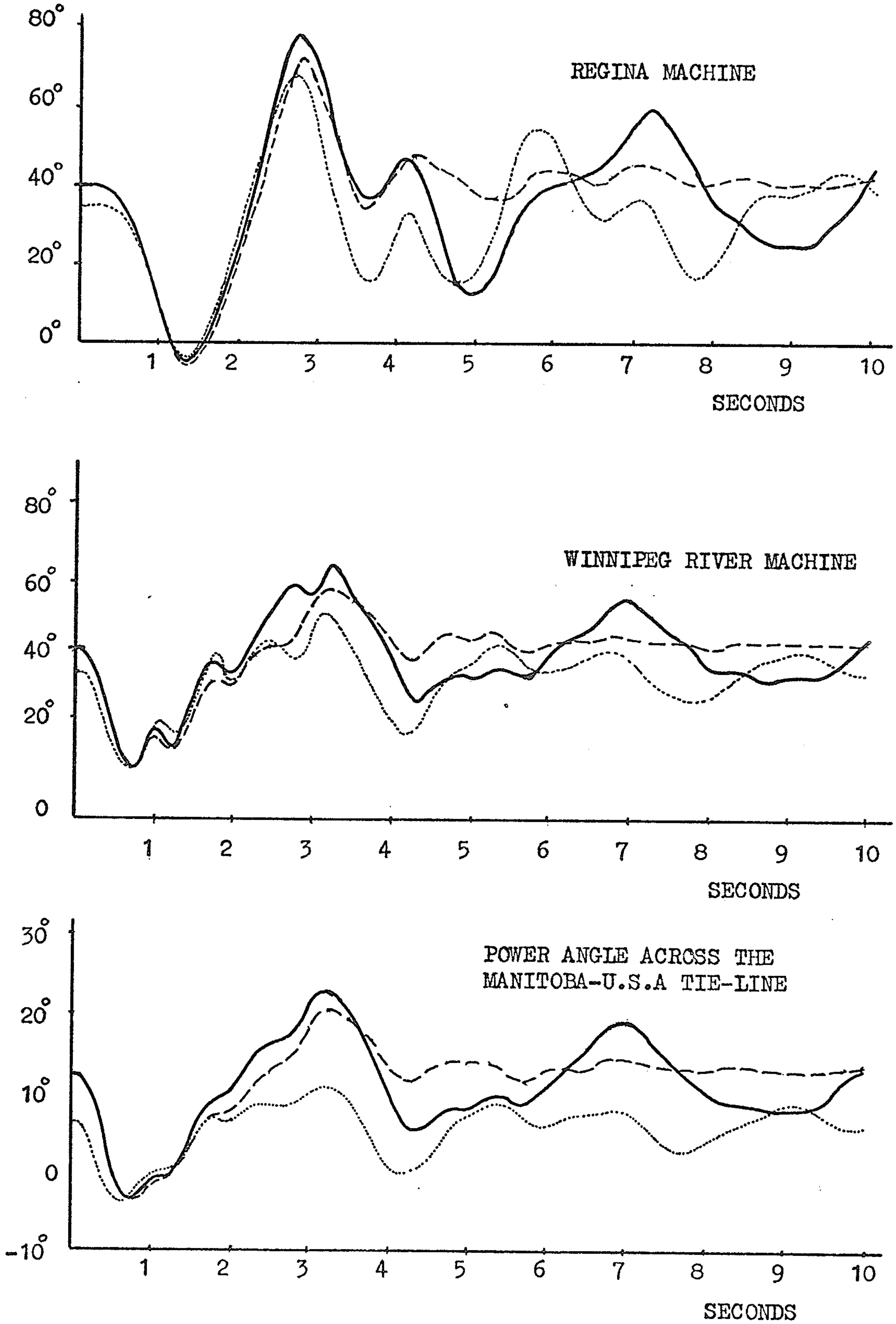


Figure 4.4 Swing curves of U.S.A-Manitoba-Saskatchewan power system model with a 0.5 second temporary block of one dc link pole (225 MW) . Cases are; 1 ——— no dc link ac system damping, 2 ·········· no dc damping but with two parallel Manitoba-U.S.A tie-lines, 4 - - - - dc link ac system damping in use.

Case 1. No dc link ac system damping.

Case 2. No dc link ac system damping, but with two parallel Manitoba-U.S.A. tie-lines.

Case 3. No dc link ac system damping, but with one Manitoba-U.S.A. tie-line and two parallel Manitoba-Saskatchewan tie-lines.

Case 4. dc link ac system damping in use and only one Manitoba-U.S.A. tie-line and one Manitoba-Saskatchewan tie-line.

Note, that for Fault 1, Case 3 was not examined. Furthermore, although the swing curves for all machines of the 12 machine model system were computed, only two are plotted in Figures 4.3 and 4.4, as they are representative of the others. The U.S.A. power system was found to remain stable.

In Figure 4.5, the per unit speed of the sending end machines is shown for each fault condition.

4.4 Discussion on use of dc link.

The important conclusions from the dc link fault study are:

4.4.1 An asynchronous tie. For best utilization of the dc link, the ac systems at each end should be asynchronous. Any parallel ac transmission would limit the capabilities of the dc link as an inertia generator.

4.4.2 AC system controls. The ac system controls on the dc link enable it to operate as an inertia

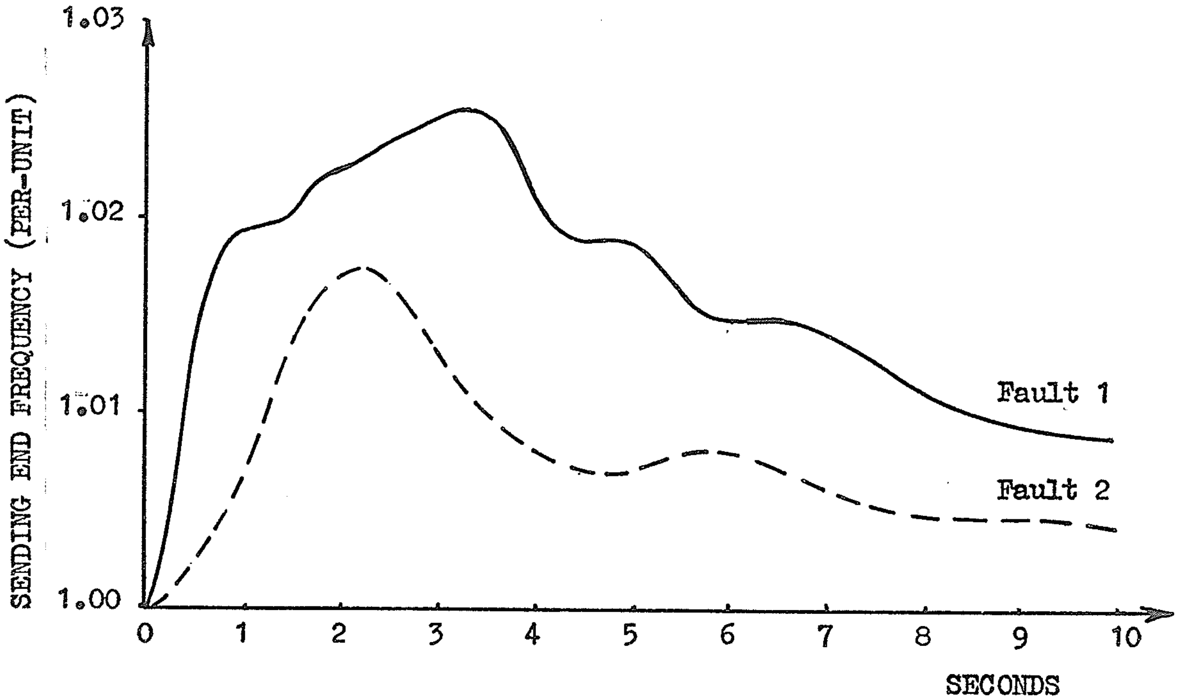


Figure 4.5 Per unit speed of the sending end machines following fault 1 and fault 2. Speed control entirely by dc link damping controls.
Fault 1: 0.5 sec. temporary block of 2.25 pu MW at Winnipeg.
Fault 2: Permanent loss of 2.0 pu MW load at Regina.

generator supplying damping power to the ac system and improving the stability of adjacent tie-lines. The ac system controls also act to control the overspeed of the sending end machines even to the extent of effectively over-riding sending end governors.

4.4.3 Remote effect of ac system controls. The stability of a tie-line not immediately close to the dc link terminal is still significantly improved by the ac system damping controls. For example, consider the Fault 2 at Regina which severely disturbs the Saskatchewan power system. Without ac damping controls on the dc link, the peak power angle swing across the Manitoba-Saskatchewan tie-line between Brandon and Boundary Dam was 61.2 degrees, and with the damping controls this angle was 56.4 degrees. Perhaps this improvement in stability is reflected more by studying the peak power angle swing of the Squaw Rapids machine which is the furthest generator from the dc link in the Saskatchewan system. Without dc link damping, the maximum power angle swing of the Squaw Rapids machine was to 229.9° from the U.S.A. infinite busbar, while only 184.4° with the dc link damping. It is of interest to also record the maximum change in dc power needed to provide this damping. For the 200 MW loss of load at Regina, the peak dc damping power added at Winnipeg was 88.6 MW. For the 225 MW, 0.5 seconds temporary block of the dc link, the post fault peak dc damping power was 62.7 MW.

4.4.4 Representing dc link damping controls in stability studies. It is important to consider the dc link damping in power system stability studies if a dc link is in operation within the region of the power system being studied. For example, if stability studies of the northern Manitoba or Saskatchewan ac power systems are being undertaken, dc link damping may play a significant contribution to its stability even though the Winnipeg terminal is relatively removed from northern Manitoba and Saskatchewan.

4.4.5 DC link as a real power controller. The effectiveness of the dc link as an ac system transient stability controller is dependent upon, firstly, the nature of the fault, i.e. whether it results from loss of load or loss of generation and, secondly, to what extent the dc link is loaded just prior to the fault. When the fault is loss of load, the excess generation tends to cause ac system overspeed and can easily be biased off by the dc link normally feeding into the ac system. However, if the fault is due to loss of generation, the dc link is limited in making up power because of current limits on its controls. Consequently, if the dc link is fully loaded just prior to the fault, it is unable to supply any additional power, but can reduce power easily. The swing curves in Figures 4.3 and 4.4 show this where the loss of load fault is more effectively compensated by the dc link than the temporary block case.

4.4.6 Delaying construction of additional ac transmission. Constructing an additional ac line in parallel to a tie-line is one method of strengthening a power system. For example, with the 200 MW load loss fault in Regina, the peak power angle swing across the Manitoba-Saskatchewan tie-line when two lines were in parallel for the inter-connection was only 34.5° compared with 61.2° with only one line, and 56.4° when the dc link damping was taken into account. In addition, considering the Squaw Rapids machine as before, its maximum power angle swing was 182.9 degrees from the U.S.A. infinite busbar when two lines in parallel existed for the Manitoba-Saskatchewan intertie and with no dc link damping. With one line and dc damping, the Squaw Rapids machine swung to a peak of 184.4 degrees from the U.S.A. infinite machine. This result is an indication of the capability of real power damping in a power system. However, the complete picture of how dc link damping compares with having two lines in parallel between Manitoba and Saskatchewan for the Saskatchewan machines is shown in the following Table 4.1 where peak power angle swing of each machine with respect to the U.S.A. infinite busbar is recorded following Fault 2.

Machine	Peak Transient Power Angle with Respect to U.S.A. with One or Two Manitoba-Saskatchewan tie-lines.		
	1 Line No dc damping	2 Lines No dc damping	1 Line and dc damping
Boundary Dam	187.6	147.6	159.7
Regina	192.35	155.3	160.9
Coteau Creek	193.3	149.1	159.4
A.L. Cole & Q.E.	200.3	153.9	172.5
Squaw Rapids	229.9	182.9	184.4

Table 4.1 Comparison of peak swing angle of Saskatchewan generators following Fault 2.

Thus, these results tend to confirm the statement of E. W. Kimbark in Chapter 1 2, that building additional transmission lines to strengthen tie-lines may be "unnecessary if equally effective but cheaper methods are available." The dc link or any inertia generator or tie-line controller may be effective in acting to strengthen ac tie-lines sufficiently to postpone construction of parallel ac transmission.

4.5 Line compensation and tie-line controllers.

A power system may have several tie-lines feeding into it. A tie-line controller on one interconnection will also act to assist another tie-line to a separate power system. If a new tie-line is to be constructed, and if it will normally require compensation - say, series compensation, then the effect of nearby tie-line controllers will improve its stability capability. This improved stability can be considered with a dollar value.

Consider the example of the 500 KV single circuit tie-line of 400 miles to be built with series compensation to transmit 1000 MW. From Section 3.5.1 of Chapter 3 it was found that 51% series compensation was required for steady state full load operation with a power angle across the Thevenin sources of $\delta = 30^{\circ}$. From stability studies taking into account the damping effect of tie-line controllers and inertia generators, the desired stability limits for the 500 KV tie-line could possibly be maintained if the power angle across it was increased to, say, 34° for normal full load operation. In other words, generally the normal operating power angle across a fully loaded transmission line including Thevenin sources is approximately 30°. This angle could be increased, maintaining the same transient stability limits if a tie-line controller or inertia generator were nearby in the ac system.

With $\delta = 34^{\circ}$, the percentage series compensation in the 400 KV tie-line can be reduced. Using Equation 1.1 and taking into account compensation efficiency of K = 0.9, and series line reactance of 0.927 p.u. ohms, the percentage series compensation is found to be 44% which is 7% less than the series compensation required with $\delta = 30^{o}$. This saving in series compensation is significant. A similar saving would be reflected in the capacitive requirements of a shunt tie-line controller designed for this transmission line in place of series compensation.

4.6 Benefits of tie-line controllers.

A tie-line controller improves the stability of not just the tie-line, but also the power system in general. It is difficult to attach a dollar value to all the benefits of tie-line controllers, but the one thing to be emphasized is that if used in a power system, they should be included in stability studies so that their true effect can be appreciated. In Manitoba, full use should be made of the dc link ac system damping capability, for possibly its full value is not yet comprehended.

CHAPTER 5

CONCLUSIONS WITH SUGGESTIONS FOR FURTHER DEVELOPMENT

5.0 Conclusions.

Several schemes and ideas for improving stability between interconnected power systems were presented and studied in this thesis. The main factors leading to improving transient stability across a tie-line were shown to be firstly, reducing effective tie-line series reactance and secondly, adding or subtracting real power from the power system to provide damping.

5.0.1 Reactive power control. Reactive tie-line control and compensation is achieved with line series and shunt reactive and capacitive devices. Methods for determining maximum reactive power rating of these devices for steady state and peak transient conditions were developed.

5.0.2 Static compensator. The saturable reactor and its part in shunt static compensation of transmission lines was explained. Also a method for designing the ratings of the reactive components of shunt compensators was presented. A comparison was made between series compensation and shunt static compensation of a tie-line for the same transient stability limit. It was found that the capacitive reactive power requirement for totally shunt compensated schemes was less than the reactive power requirement for series capacitors. However the saturable reactor must have the inductive capacity to absorb all the peak shunt capacitive reactive power unless the shunt capacitors are only briefly switched onto the line during transient disturbances.

5.0.3 Variable reactor. As an alternative to the saturable reactor, a variable reactor was proposed. The advantage of this device compared with the saturable reactor is the better utilization of capacitors and inductors resulting in significant cost benefits. It is envisaged that the variable reactor as a shunt compensating device in tie-lines will be very competitive with series compensation and switched series capacitors.

5.0.4 Positioning of shunt reactance controller. A study was conducted indicating that shunt tie-line compensators and controllers are most effective at the transmission line equivalent mid-point. However for very long lines, one shunt device at the line centre may not be effective and an optimum system will have more than one shunt controller each equally spaced along the line.

5.0.5 Real power control. Several real power controllers were studied. Transiently a synchronous condensor acts as a real power controller since it is able to improve transient stability by contributing to system damping and increased inertia as well as providing voltage support. For synchronous condensors attached to transmission lines it was emphasised that excitation control techniques can be useful in further improvements in system transient stability. Of the inertia controllers discussed, the dc link is the most effective for controlling real power - even if it is not being used as a tie-line. It was recommended that ac system damping controls associated with the dc link be fully utilized.

5.0.6 DENA program. A stability program (Appendix II) has been developed for evaluating performance of ac system controllers and allowing continual changes in the transmission network to occur dynamically without repeated network matrix inversions. Using this program, design and optimization of tie-line controller functions can be determined with simple trial and error tests. This program is not expensive to run on digital computer if a reduced ac system representation is modelled.

5.1 Areas of further development.

A study that has endeavored to clarify or introduce new concepts is incomplete unless areas for further development are suggested.

5.1.1 Fast acting low voltage switch. The variable reactor proposed herein is subject to the development of a fast acting low voltage switch. Development of the hvdc switching device as described in reference [17] indicates that the mechanical duties of such a switch are indeed possible. This switch must operate to make and break reactive circuits and also minimize switching transients. Use of thyristors as switches is one means of overcoming these problems. Thyristors can also be used to regulate current through the reactive devices, but doing so will necessitate filters, thus increasing costs.

5.1.2 Combining the variable reactor with the saturable reactor. If the fast acting low voltage switch is indeed a realistic possibility, then a further development in shunt control and compensation would be to combine the variable reactor and the saturable reactor. This could be done by placing a small saturable reactor in the low voltage secondary circuit of the variable reactor transformer. The variable reactor would then maintain the constant voltage characteristic of the static compensator through judicious switching and control of the other secondary circuit capacitors and air cored reactors. By this means the saturable reactor as an expensive item would be kept small yet still have control of the voltage.

5.1.3 Optimization studies. Further studies that could follow the proposals of this thesis would be the optimization of shunt compensator and control design. Detailed optimization of proposals have been beyond the scope of this study. Reliability of various tie-line control schemes could also be investigated to complement optimization studies.

5.1.4 Harmonic resonances. With shunt compensated transmission lines a danger of harmonic resonance conditions exist which need investigating for the variable reactor application.

5.1.5 Dc link controls. High voltage direct current transmission is still in its infancy. Studies in multi-terminal dc schemes and the use of ac system damping controls would be an area of useful investigation.

5.1.6 Central control. The question of central digital control for a power system is sometimes raised. With a system disturbance, the central computer is to analyze the situation and issue the optimal commands to controllers distributed throughout the system. Problems exist in fast computing and fast telemetry equipment required.

As the demand for better control in ac power systems increases, it is anticipated that the controllers and techniques discussed herein will be seriously considered by the power system planning engineer.

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APPENDIX I

THREE MACHINE UNDAMPED POWER SYSTEM MODEL

To evaluate the effect of series and shunt tie-line controllers, a simple three machine undamped power system digital model was developed as shown in Figure A1.

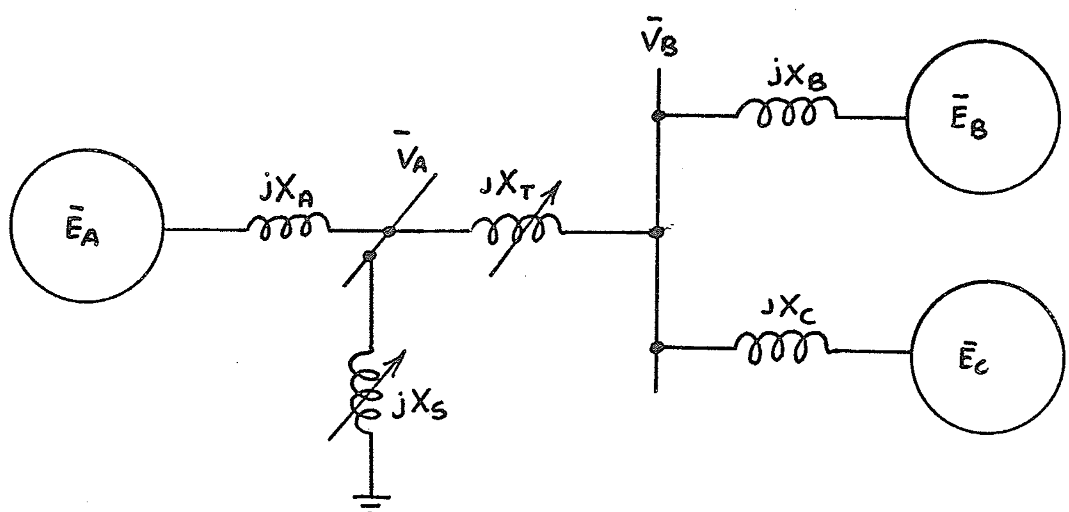

Figure A1. Three machine undamped power system model.

The node equations in terms of d-axis (real) and q-axis (imaginary) are,

$$\bar{V}_A = V_{Ad} + jV_{Aq}$$

$$= \frac{E_{Ad}}{X_A} X_D + \frac{V_{Bd}}{X_T} X_D + j\left[\frac{E_{Aq}}{X_A} X_D + \frac{V_{Bq}}{X_T} X_D\right] \qquad \text{(AI-1)}$$

$$\overline{V}_B = V_{Bd} + jV_{Bq}$$

$$= \frac{\left[\frac{E_{Bd}}{X_A} + \frac{E_{Cd}}{X_C} + \frac{E_{Ad}\cdot X_D}{X_A \cdot X_T}\right] + j\left[\frac{E_{Bq}}{X_B} + \frac{E_{Cq}}{X_C} + \frac{E_{Aq}\cdot X_D}{X_A \cdot X_T}\right]}{\left[\frac{1}{X_E} - \frac{X_D}{X_T \cdot X_T}\right]}, \quad \text{(AI-2)}$$

where $X_D = \dfrac{1}{\frac{1}{X_A} + \frac{1}{X_S} + \frac{1}{X_T}}$,

and $X_E = \dfrac{1}{\frac{1}{X_T} + \frac{1}{X_C} + \frac{1}{X_B}}$

The power P_T from each machine is simply found from the volt and current product of similar d and q axis components at machine terminals. Voltage angles at each machine rotor are determined by:

$$\frac{377}{2H}\iint (P_M - P_T)\, dt.dt ,$$

where P_T = Electric power generated,

P_M = Mechanical power to generator,

H = Inertia constant MW-secs/MVA.

One advantage of this simple model is that reactances can be changed or controlled as desired during the continuous solution. Furthermore, little modification is required to the equations to accommodate the d and q axis equations of a fully represented synchronous condensor. The IBM continuous system modelling program [18] was used as the modelling tool since analogue control blocks can be easily adapted with its use.

APPENDIX II

DIGITAL ELECTRICAL NETWORK ANALOGUE PROGRAM FOR POWER SYSTEM STABILITY AND CONTROL STUDIES.

The digital electrical network analogue (DENA) program is an iterative and dynamic power system program which allows network parameters (such as transmission lines) to be updated every time step in the solution. It was developed using IBM's continuous system modelling program (CSMP) which allows analogue blocks to be formed for modelling machine exciters and governors or any other control equipment [18]. The DENA program is dimensioned to 25 synchronous machines and 100 transmission lines, but can be expanded if necessary.

Three main assumptions of the program are firstly, lossless transmission lines are modelled. Secondly, loads are considered constant power loads. Thirdly, the voltage of a network busbar is estimated from an empirical function of its angle relative to the voltage angle of adjacent busbars to which it is linked through transmission lines. The mathematical basis of the program is as follows:

A transmission line of equivalent series reactance X_{ij} between busbars i and j helps define a power angle function L_{ij},

$$\frac{P_{ij}}{\delta_{ij}} = L_{ij} = \frac{E_i . E_j . \text{Sin}\,\delta_{ij}}{X_{ij} \cdot \delta_{ij}} , \qquad \text{(AII-1)}$$

where P_{ij} = transmission line power

δ_{ij} = voltage angle difference between busbars i and j

E_i, E_j = voltage magnitudes at respective busbars.

Thus, at a system network busbar to which only transmission lines and electrical loads are connected, it is possible to determine the voltage angle δ_i of busbar 'i' if all the power angle functions L_{ij} for each transmission line and voltage angles δ_j of the immediately adjacent busbars are known

$$\delta_i = \frac{\sum_{j=1}^{a} \delta_j . L_{ij} + P_{di}}{\sum_{j=1}^{a} L_{ij}} , \qquad \text{(AII-2)}$$

where P_{di} = load power at busbar 'i'.

By solving this equation at each network busbar in turn for the fixed time step, an iterative solution for busbar voltage angles can be obtained. A suitable convergence technique is used to accelerate the solution.

Busbar voltage magnitudes, however, are approximated with a resulting error in solution. Initial steady state busbar voltage magnitudes and angles are determined from a load flow study.

The busbar voltage magnitudes during the dynamic solution are estimated with an approximation technique as,

$$E_i = f\left(\sum_{j=1}^{a} |\delta_{ij}|\right) \qquad \text{(AII-3)}$$

As the angles δ_{ij} (which are the voltage angles across the transmission lines radiating from bus 'i') increase, then the voltage magnitude E_i decreases as a function which is cosine in nature.

To represent synchronous machines, the power angle relationship is derived from Reference [11] as,

$$L_m = \frac{P}{\delta m}$$

$$= E_i^{\,2}\left[\frac{1}{X_q \quad X_L} - \frac{1}{X_q' + X_L}\right] \cdot \frac{\text{Sin } 2\delta_m}{2\delta_m} + \frac{E_i E_q'}{X_d' + X_L} \cdot \frac{\text{Sin } \delta_m}{\delta_m}$$

(AII-4)

where E_q' = q-axis machine internal voltage behind quadrature transient reactance

X_L = any series reactance between machine terminals and busbar 'i', e.g. transmission line and transformer leakage reactance

δ_m = power angle in radians between E_q' and busbar 'i'

E_i = busbar voltage magnitude

X_q = q-axis synchronous reactance

X_d' = d-axis synchronous reactance.

The initial value of E'_q can be found, firstly, by differentiating Equation AII-4,

$$\frac{\partial P}{\partial \delta_m} = E_i^2 \left[\frac{1}{X_q + X_L} - \frac{1}{X'_d + X_L}\right] \cos 2\delta_m + \frac{E_i E'_q}{X'_d + X_L} \cos \delta_m$$

(AII-5)

From Reference [3], J.D. Ainsworth has derived this same expression in a different form, <u>i.e.</u>,

$$\frac{\partial P}{\partial \delta_m} = Q_o + \frac{E_i^2 \cos^2 \delta_m}{X_q + X_L} + \frac{E_i^2 \sin^2 \delta_m}{X'_d + X_L}, \qquad \text{(AII-6)}$$

where Q_o = reactive power generated by the machine.

Equating Equations AII-5 and AII-6 enable a value for E'_q to be obtained.

Machine damping is based on the classical damping expression for synchronous machines derived using induction motor theory

$$R = E_i^2 \left\{ T_d'' \left[\frac{1}{X''_d + X_L} - \frac{1}{X'_d + X_L}\right] \sin^2 \delta_m + T''_q \left[\frac{1}{X''_q + X_L} - \frac{1}{X_q + X_L}\right] \cos^2 \delta_m \right\},$$

(AII-7)

such that damping power = $R.\frac{d\delta_m}{dt}$,

where T''_d, T''_q = d,q-axis subtransient short circuit time constants which include effect of X_L

X''_d, X''_q = d,q-axis subtransient reactances.

The synchronous machine representation can now be expressed in terms of R and L_m,

Damping power + Synchronising power = Air gap power,

or,

$$R.\frac{d\delta_m}{dt} + L_m.\delta_m = P_T \,, \qquad \text{(AII-8)}$$

where P_T = Air gap power

$\delta_m = \delta_q - \delta_i$

δ_q = angle of the machine rotor relative to a fixed arbitrary frame of reference

δ_i = angle of busbar to which machine is attached relative to the same frame of reference.

Therefore,

$$R.\frac{d(\delta_q - \delta_i)}{dt} + L_m(\delta_q - \delta_i) = P_T \qquad \text{(AII-9)}$$

Now, air gap power P_T of the machine can be determined relative to all adjacent busbars directly connected to the busbar 'i' to which the machine is attached,

$$P_T = \sum_{j=1}^{a} \delta_j.L_{ij} - \delta_i \sum_{j=1}^{a} L_{ij}, \qquad \text{(AII-10)}$$

where a = total number of adjacent busbars to busbar 'i'.

Solving for δ_i which is the voltage angle of busbar 'i' from equations AII-9 and AII-10,

$$\delta_i = \frac{\frac{1}{R}\sum_{j=1}^{a}\delta_j . L_{ij} + \delta_q . \frac{L_m}{R} + \frac{d\delta_q}{dt}}{\frac{d}{dt} + \frac{L_m}{R} + \frac{1}{R}\sum_{j=1}^{a} L_{ij}} , \qquad \text{(AII-11)}$$

if $\frac{L_m}{R} + \frac{1}{R}\sum_{j=1}^{a} L_{ij}$ is large, and for normal power systems it has the magnitude of 200 to 300 seconds^{-1}, indicating a subtransient effect, the expression for machine busbar voltage angle then is,

$$\delta_i = \frac{\sum_{j=1}^{a}\delta_j . L_{ij} + \delta_q . L_m + \frac{R . d\delta_q}{dt} + P_{di}}{L_m + \sum_{j=1}^{a} L_{ij}} \qquad \text{(AII-12)}$$

This expression is used in the iterative process which considers busbars to which machines are attached in rotating sequence to improve solutions for the terminal busbar voltage angles δ_i. P_{di} which has been added to Equation AII-12 represents power to any load on busbar 'i'.

Each machine rotor velocity is found at the completion of the total iteration process as,

$$\frac{d\delta_q}{dt} = \frac{1}{2H}\int_c (P_m - P_T)\, dt , \qquad \text{(AII-13)}$$

where $H =$ rotor inertia constant in MW-seconds/MVA

$P_m =$ mechanical shaft power.

A further integration gives rotor angle δ_q. Integration is by Simpsons' method.

The iteration procedure is based on Equations AII-2 and AII-12 and continues until error in solution is reduced to less than a specified amount. The parameters of each of these two equations are updated at the end of the iteration procedure at each time step.

A flow chart of the computation process is shown in Figure A2. A listing of the DENA program is included in this Appendix. A typical job time on the University of Manitoba's IBM/360 computer for the thirteen machine power system with dc link and controls as depicted in Figure 3.3 was 4.8 minutes (including compiling time) for 20 seconds of real time at 0.01 seconds time step.

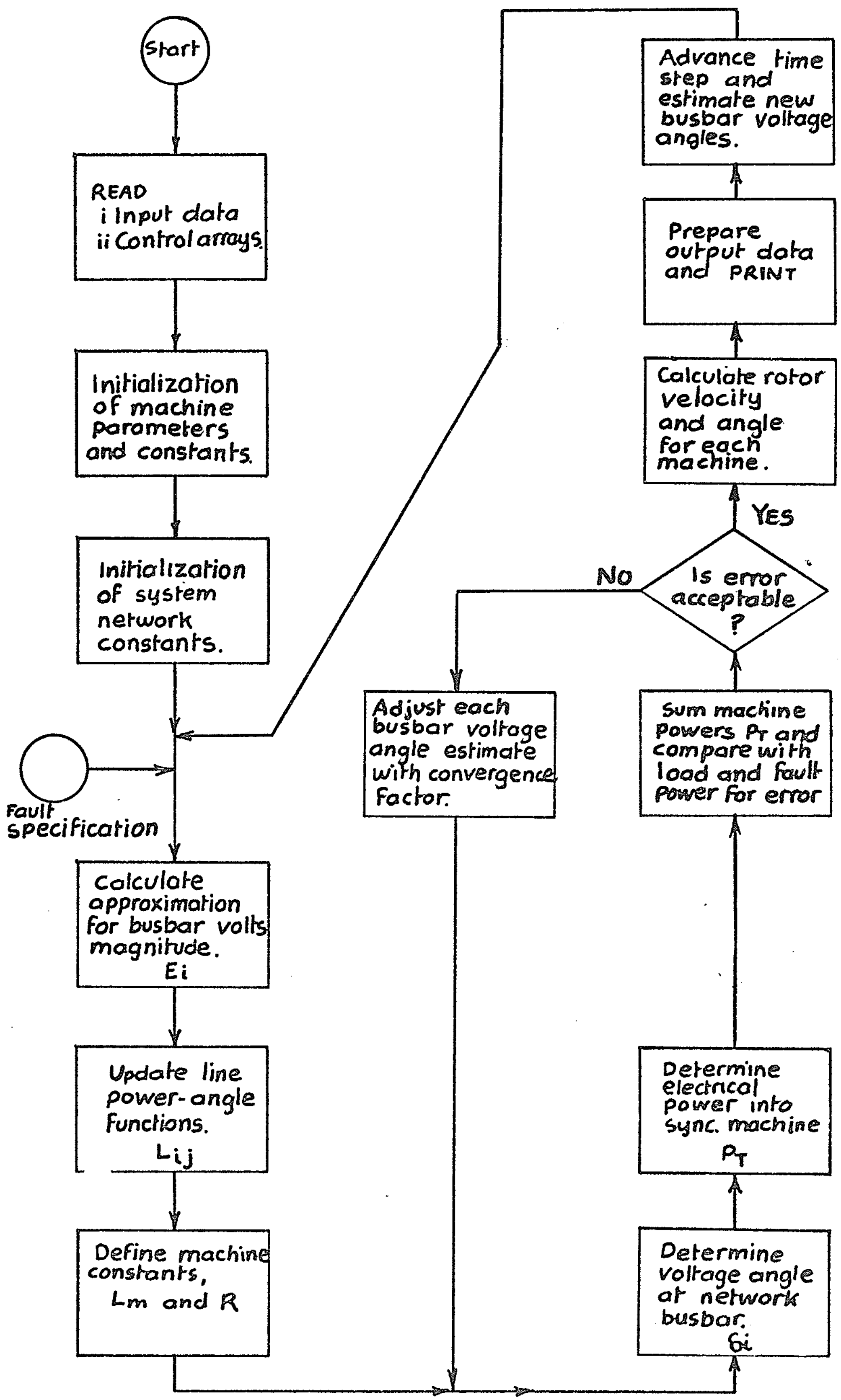

Figure A2 Computation process for DENA program.

APPENDIX II Continued.

Listing of DENA program modeling the U.S.A.-Manitoba-Saskatchewan power system as shown in Figure 3.3, page 44.

```
                    ****CONTINUOUS SYSTEM MODELING PROGRAM****

          ***PROBLEM INPUT STATEMENTS***

LABEL         DIGITAL EQUIVALENT ELECTRICAL NETWORK ANALOGUE
FIXED NB, NTOTAL, MX, L2X, I1, I2, I3, I4, I5, I6, I7, I8, MB, I8, IFB
*BUSBAR DEFINITION
CONST NB=4, MB=12, NTOTAL=16
*MACHINE AND LINE DEFINITION
CONST MX=12, L2X=40, I8=30
*SYSTEM FREQUENCY
CONST WO=377.0
*NETWORK EMPIRACLE CONSTANTS
CONST KN=0.7, KE1=0.3
*FAULT SPECIFICATION
CONST TON=0.10, TOFF=10.0, FAULTM=2.0,  DX=0.010, FFB=5.0
STORAG AN(40),AM(40),ANM(13),TL(40),VB(16),AB(16),PM(12),QM(12),...
       XD(12),XQ(12),XDP(12),TDPP(12),TQOPP(12),H(12),XDPP(12),XQPP(12)
TABLE  AN(1)=2.,AN(2)=3.,AN(3)=8.,AN(4)=1.,AN(5)=7.,AN(6)=8.,...
       AN(7)=1.,AN(8)=4.,AN(9)=7.,AN(10)=9.,AN(11)=10.,AN(12)=3.,...
       AN(13)=11.,AN(14)=12.,AN(15)=6.,AN(16)=13.,AN(17)=5.,AN(18)=7.,...
       AN(19)=14.,AN(20)=2.,AN(21)=3.,AN(22)=6.,AN(23)=1.,AN(24)=2.,...
       AN(25)=16.,AN(26)=3.,AN(27)=10.,AN(28)=3.,AN(29)=9.,AN(30)=4.,...
       AN(31)=12.,AN(32)=4.,AN(33)=11.,AN(34)=5.,AN(35)=14.,AN(36)=6.,...
       AN(37)=13.,AN(38)=15.,AN(39)=14.,AN(40)=8.
TABLE  AM(1)=1.,AM(2)=1.,AM(3)=1.,AM(4)=2.,AM(5)=2.,AM(6)=2.,...
       AM(7)=3.,AM(8)=3.,AM(9)=3.,AM(10)=3.,AM(11)=3.,AM(12)=4.,...
       AM(13)=4.,AM(14)=4.,AM(15)=5.,AM(16)=5.,AM(17)=6.,AM(18)=6.,...
       AM(19)=6.,AM(20)=7.,AM(21)=7.,AM(22)=7.,AM(23)=8.,AM(24)=8.,...
       AM(25)=8.,AM(26)=9.,AM(27)=9.,AM(28)=10.,AM(29)=10.,AM(30)=11.,...
       AM(31)=11.,AM(32)=12.,AM(33)=12.,AM(34)=13.,AM(35)=13.,...
       AM(36)=14.,AM(37)=14.,AM(38)=14.,AM(39)=15.,AM(40)=16.
TABLE  TL(1)=.1185,TL(2)=.064,TL(3)=.0815,TL(4)=.1185,TL(5)=.416,...
       TL(6)=.39,TL(7)=.064,TL(8)=.2046,TL(9)=.115,TL(10)=.029,...
       TL(11)=.032,TL(12)=.2046,TL(13)=.328,TL(14)=.2,TL(15)=.0553,...
       TL(16)=.249,TL(17)=.0553,TL(18)=.2549,TL(19)=1.002,TL(20)=.416,...
       TL(21)=.115,TL(22)=.2549,TL(23)=.0815,TL(24)=.39,TL(25)=.5117,...
       TL(26)=.029,TL(27)=.148,TL(28)=.032,TL(29)=.148,TL(30)=.328,...
       TL(31)=.05,TL(32)=.2,TL(33)=.05,TL(34)=.249,TL(35)=.22,...
       TL(36)=1.002,TL(37)=.22,TL(38)=.1487,TL(39)=.1487,TL(40)=.5117
TABLE  VB(1)=1.05,VB(2)=1.034,VB(3)=1.03,VB(4)=1.02,VB(5)=1.0,...
       VB(6)=1.015,VB(7)=1.08,VB(8)=1.008,VB(9)=1.04,VB(10)=1.1,...
       VB(11)=1.02,VB(12)=1.02,VB(13)=1.03,VB(14)=1.012,VB(15)=1.0,...
       VB(16)=1.0,AB(1)=22.,AB(2)=18.,AB(3)=20.,AB(4)=8.,...
      AB(5)=17.7,AB(6)=29.,AB(7)=15.,AB(8)=33.,AB(9)=18.,...
       AB(10)=20.,AB(11)=38.,AB(12)=0.0,AB(13)=15.3,AB(14)=15.,...
       AB(15)=35.7,AB(16)=21.0
TABLE  ANM(1)=5.,ANM(2)=6.,ANM(3)=7.,ANM(4)=8.,ANM(5)=9.,...
       ANM(6)=10.,ANM(7)=11.,ANM(8)=12.,ANM(9)=13.,ANM(10)=14.,...
       ANM(11)=15.,ANM(12)=16.,ANM(13)=5000.0,...
       PM(1)=.238,QM(1)=.2,XD(1)=2.8,XQ(1)=2.6,XDP(1)=.3982,...
       XDPP(1)=.32,XQPP(1)=.32,TDPP(1)=.029,TQOPP(1)=.12,H(1)=5.41,...
       PM(2)=3.46,QM(2)=-.3,XD(2)=.122,XQ(2)=.09,XDP(2)=.0635,...
       XDPP(2)=.051,XQPP(2)=.061,TDPP(2)=.028,TQOPP(2)=.035,H(2)=21.14
TABLE  PM(3)=2.62,QM(3)=.19,XD(3)=.6,XQ(3)=.50,XDP(3)=.1005,...
       XDPP(3)=.07,XQPP(3)=.07,TDPP(3)=.03,TQOPP(3)=.12,H(3)=12.23,...
       PM(4)=4.1,QM(4)=-.6,XD(4)=.12,XQ(4)=.09,XDP(4)=.0637,...
       XDPP(4)=.05,XQPP(4)=.061,TDPP(4)=.028,TQOPP(4)=.04,H(4)=25.4,...
       PM(5)=.95,QM(5)=.1,XD(5)=1.5,XQ(5)=1.42,XDP(5)=.2042,...
       XDPP(5)=.17,XQPP(5)=.17,TDPP(5)=.03,TQOPP(5)=.12,H(5)=8.98,...
       PM(6)=5.6,QM(6)=-1.9,XD(6)=.12,XQ(6)=.08,XDP(6)=.0593,...
      XDPP(6)=.03,XQPP(6)=.045,TDPP(6)=.03,TQOPP(6)=.035,H(6)=17.95
TABLE  PM(7)=8.91,QM(7)=.4,XD(7)=.11,XQ(7)=.10,XDP(7)=.024,...
       XDPP(7)=.02,XQPP(7)=.02,TDPP(7)=.03,TQOPP(7)=.12,H(7)=45.89,...
        PM(9)=1.62,QM(9)=.1,XD(9)=.4,XQ(9)=.3,XDP(9)=.178,...
       XDPP(9)=.09,XQPP(9)=.11,TDPP(9)=.03,TQOPP(9)=.035,H(9)=6.93,...
       PM(10)=1.46,QM(10)=.13,XD(10)=.7,XQ(10)=.65,XDP(10)=.101,...
       XDPP(10)=.06,XQPP(10)=.06,TDPP(10)=.03,TQOPP(10)=.12,H(10)=16.,...
       PM(11)=2.48,QM(11)=-.26,XD(11)=.3,XQ(11)=.2,XDP(11)=.094,...
       XDPP(11)=.06,XQPP(11)=.07,TDPP(11)=.03,TQOPP(11)=.035,H(11)=13.7
TABLE  PM(12)=2.02,QM(12)=0.2,XD(12)=0.35,XQ(12)=.28,XDP(12)=.1084,...
       XDPP(12)=.08,XQPP(12)=.09,TDPP(12)=.03,TQOPP(12)=.04,H(12)=9.2,...
       PM(8)=0.01,QM(8)=0.0,XD(8)=0.0,XQ(8)=0.01
*TRANSMISSION LINE PARAMETERS
CONST TT34=0.1023, TT67=0.2549
```

```
INITIAL
NOSORT
/      DIMENSION D1(25), RK1(25), RK2(25), XC(25), VMO(25), VMP(25)
/      DIMENSION DT(25), VK3(25), VK4(25), VK5(25), VK6(25), VK7(25)
/      DIMENSION VK8(25), L(30,30), DAB(30), DI(30), ABR(30), VNM(10)
/      DIMENSION X(25), R(25), DIM(25), DDAB(30), LK1(25)
/      DIMENSION VK1(25), DAM(25),  VV(25)
       IFB=FFB
       DO 10 I1=1,MX
       IF (I1.GT.1) GO TO 11
       I2=ANM(I1)
       GO TO 12
    11 IF (ANM(I1-1).EQ.ANM(I1)) GO TO 12
       I2=I2+1
    12 TAND=PM(I1)/(QM(I1)+VB(I2)*VB(I2)/XQ(I1))+1.0E-6
       D1(I1)=ATAN(TAND)
       IF (XD(I1).LT.1.0E-8) GO TO 13
*MACHINE DAMPING QUANTITIES
       TQPP=TQOPP(I1)*XQPP(I1)/XQ(I1)
       RK1(I1)=TDPP(I1)*(1.0/XDPP(I1)-1.0/XDP(I1))
       RK2(I1)=TQPP*(1.0/XQPP(I1)-1.0/XQ(I1))
*INERTIA SUSCEPTANCE
       XC(I1)=0.5*HO/H(I1)
*MACHINE SYNCHRONIZING TORQUE QUANTITIES
       LK1(I1)=1.0/XQ(I1)-1.0/XDP(I1)
*MACHINE BUSBAR VOLTAGE CONSTANTS
       B4=COS(D1(I1))
       B5=SIN(D1(I1))
       VMP(I1)=QM(I1)/B4+VB(I2)*VB(I2)*(B4/XDP(I1)+B5*TAND/XQ(I1))
       GO TO 9
    13 B4=COS(D1(I1))
       VMP(I1)=(QM(I1)/VB(I2)+VB(I2)/XQ(I1))/B4
     9 B2=KE1*D1(I1)
       B3=COS(B2)
       VMO(I1)=VB(I2)/B3
*INITIALIZATION OF MACHINE CONSTANTS
       VK1(I1)=0.0
       VK7(I1)=0.0
       VK8(I1)=0.0
       DIM(I1)=0.0
       DAM(I1)=0.0
    10 DT(I1)=D1(I1)
*INITIALIZATION OF NETWORK CONSTANTS
       DO 14 I1=1,NTOTAL
       DO 15 I2=1,NTOTAL
    15 L(I1,I2)=1.0E-8
       DI(I1)=0.0
       DAB(I1)=0.0
       DDAB(I1)=0.0
    14 ABR(I1)=AB(I1)/57.296
       DO 8 I1=1,L2X
       I2=AN(I1)
       I3=AM(I1)
     8 L(I2,I3)=1.0
       DO 16 I1=1,VB
       C4=1.0E-8
       C1=0.0
       DO 17 I2=1,NTOTAL
       IF (L(I1,I2).LT.0.1) GO TO 17
       C2=ABR(I2)-ABR(I1)
       C3=ABS(C2)
       C1=C1+C3
       C4=C4+1.0
    17 CONTINUE
       C5=KN*C1/C4
       C6=COS(C5)
       VNM(I1)=VB(I1)/C6
    16 CONTINUE
*TRANSMISSION LINE PARAMETERS
       TL(8)=TT34
       TL(12)=TT34
       TL(18)=TT67
       TL(22)=TT67
```

```
DYNAMIC
NOSORT
*FAULT DEFINITION
      D13=STEP(TON)
      D14=STEP(TOFF)
      DI(IFB)=FAULTM*(D13-D14)
      PP=0.0
*AC SYSTEM BUSBAR VOLTS
      DO 18 I1=1,NB
      C4=1.0E-8
      C1=0.0
      DO 19 I2=1,NTOTAL
      LAX=ABS(L(I1,I2))
      IF (LAX.LT.9.0E-7) GO TO 19
      C2=ABR(I2)-ABR(I1)
      C3=ABS(C2)
      C1=C1+C3
      C4=C4+1.0
   19 CONTINUE
      C5=KN*C1/C4
      C6=COS(C5)
      PP=PP+DI(I1)
   18 VV(I1)=VNM(I1)*C6
      I3=1
      I2=NB+1
      DO 101 I1=I2,NTOTAL
      B2=KE1*DT(I3)
      B3=COS(B2)
      IF (ANM(I3+1).EQ.ANM(I3)) GO TO 102
      VV(I1)=VMO(I3)*B3
      PP=PP+DI(I1)
      GO TO 101
  102 I3=I3+1
      B4=KE1*DT(I3)
      B5=COS(B4)
      VV(I1)=(VMO(I3-1)*B3+VMO(I3)*B5)*0.5
      PP=PP+DI(I1)
  101 I3=I3+1
*DEFINING LINE ANALOGUE INDUCTANCE
      DO 103 I1=1,L2X
      I2=AN(I1)
      I3=AM(I1)
      C1=ABR(I2)-ABR(I3)+1.0E-8
      SIND=SIN(C1)
  103 L(I2,I3)=VV(I2)*VV(I3)*SIND/(TL(I1)*C1)
*DEFINING MACHINE ANALOGUE INDUCTANCE AND RESISTANCE
      DO 104 I1=1,MX
      I2=ANM(I1)
      C4=VV(I2)*VV(I2)
      SIN1D=SIN(DT(I1))
      IF (XD(I1).LT.1.0E-8) GO TO 105
      C1=DT(I1)+DT(I1)
      SIN2D=SIN(C1)
      COS2D=COS(C1)
      XA1=(C4*LK1(I1)*SIN2D*0.5+VMP(I1)*SIN1D)/DT(I1)
      X(I1)=LIMIT(0.1,9.9E+6,XA1)
      C2=RK1(I1)+RK2(I1)
      C3=(RK2(I1)-RK1(I1))*COS2D
      R(I1)=2.0/(C4*(C2+C3))
      GO TO 104
  105 X(I1)=VMP(I1)*SIN1D*VV(I2)/DT(I1)
  104 CONTINUE
      I8=0
```

```
*ITERATION ROUTINE
   25 I6=1
      IB=IB+1
      B3=0.0
      PB=0.0
      DO 20 I1=1,MB
   26 DO 22 I3=1,NB
      S1=DI(I3)
      S2=0.0
      DO 23 I4=1,NTOTAL
      IF (L(I3,I4).EQ.1.0E-8) GO TO 23
      S1=S1+DAB(I4)*L(I3,I4)
      S2=S2+L(I3,I4)
   23 CONTINUE
      IF (S2.EQ.0.0) GO TO 22
      DAB(I3)=S1/S2
   22 CONTINUE
      I3=I1+NB
      S1=DI(I3)
      IF (ANM(I6+1).EQ.ANM(I6)) GO TO 31
      IF (XD(I6).LT.9.0E-7) GO TC 33
      I7=I6
      S2=0.0
      I5=0
      I6=I6+1
      GO TO 32
   31 I7=I6
      I5=I6+1
      I6=I6+2
      S2=X(I5)
      GO TO 32
   33 I7=0
      I5=I6
      S2=X(I5)
      I6=I6+1
   32 DO 21 I2=1,NTOTAL
      IF (L(I3,I2).EQ.1.0E-8) GO TO 21
   29 S1=S1+DAB(I2)*L(I3,I2)
      S2=S2+L(I3,I2)
   21 CONTINUE
      IF (S1.EQ.0.0) GO TO 48
      IF (I7.EQ.0) GO TO 46
      D24=(S1+VK1(I7)+VK8(I7)*X(I7))/(X(I7)+S2)
      B2=S1-S2*D24
      DIM(I7)=B2
   52 IF (I5.LT.1) GO TO 47
      DIM(I5)=D24*X(I5)
      B2=DIM(I5)+DIM(I7)
      GO TO 47
   46 IF (S2.EQ.0.0) GO TO 49
      D24=S1/S2
      B2=D24*X(I5)
      DIM(I5)=B2
*ERROR COMPARISON
   47 B8=D24-DAB(I3)
      B9=ABS(B8)
      PB=PB+B2
      IF (IB.LT.2) KB=0.0
      IF (IB.GE.29) KB=0.0
      DAB(I3)=D24+B9*KB
   45 IF (B9.GT.4.0E-05) GO TO 49
   48 B13=0.0
      GO TO 50
   49 B13=1.0
   50 B3=B3+B13
   20 CONTINUE
      B14=PP-PB
      B15=ABS(B14)
      B16=50.0*B14
      KB=LIMIT(-1.0,1.0,B16)
      IF (B15.LT.0.005) GO TO 63
      B3=1.0
   63 IF (IB.GE.I8) GO TO 62
      IF (B3.GT.0.5) GO TO 25
```

```
62 DO 60 I1=1,MX
   IF (XD(I1).LT.1.0E-8) GO TO 60
   G1=VK7(I1)+DX*0.5*(DIM(I1)+DAM(I1))
   G2=DX*0.5*XC(I1)*(G1+VK7(I1))
   G3=VK8(I1)+G2
   I2=ANM(I1)
   DT(I1)=G3-DAB(I2)+D1(I1)
   DAM(I1)=DIM(I1)
   VK7(I1)=G1
   VK8(I1)=G3
   VK1(I1)=G2/(R(I1)*DX)
60 CONTINUE
   DO 61 I1=1,NTOTAL
61 ABR(I1)=DAB(I1)+AB(I1)*0.01746
```

```
*OUTPUT INFORMATION
      COUNT=IB
      A1=(D1(1)+VK8(1))*57.296+AB(5)
      A2=(D1(2)+VK8(2))*57.296+AB(6)
      A3=(D1(3)+VK8(3))*57.296+AB(7)
      A4=(D1(4)+VK8(4))*57.296+AB(8)
      A5=(D1(5)+VK8(5))*57.296+AB(9)
      A6=(D1(6)+VK8(6))*57.296+AB(10)
      A7=(D1(7)+VK8(7))*57.296+AB(11)
      A9=(D1(9)+VK8(9))*57.296+AB(13)
      A10=(D1(10)+VK8(10))*57.296+AB(14)
      A11=(D1(11)+VK8(11))*57.296+AB(15)
      A12=(D1(12)+VK8(12))*57.296+AB(16)
      TL34=12.0+(DAB(3)-DAB(4))*57.296
      TL67=14.0+(DAB(6)-DAB(7))*57.296
      AB3=CAB(3)*57.296+AB(3)
*EXTRAPOLATION ESTIMATE
      DO 70 I1=1,NTOTAL
      G4=DAB(I1)
      DAB(I1)=G4+G4-DDAB(I1)
      DDAB(I1)=G4
   70 CONTINUE
SORT
TIMER DELT=0.010, FINTIM=10.0,PRDEL=0.05
PRINT COUNT,A1,A2,A3,A4,A5,A6,A7,A9,A10,A11,A12,B14,PP,TL34,AB3,...
      TL67
END
PARAMETER TT34=0.2046, TT67=0.127
END
STOP
```