DESIGN CONSIDERATIONS FOR EXTRA-HIGH-VOLTAGE TRANSMISSION SYSTEMS

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A Major Technical Report

in

The Faculty

of

Engineering

Presented in Partial Fulfillment of the Requirements
for the degree of Master of Engineering at
Concordia University
Montréal, Québec, Canada

November 1978

ABSTRACT

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This major report discusses the main considerations employed in designing any extra-high-voltage transmission system.

The voltage control problem along with series and shunt compensation associated with any a.c. system have been analyzed in steady-state and transient conditions.

The design process for determining the stability of an extra-high-voltage network in steady-state and transient state is investigated through the use of a digital computer.

The dielectric strength of external insulation along with the interaction of electrical and mechanical criteria on the behaviour of the bundles conductors are discussed.

Also some of the more important factors entering into substation design with substation single-line diagrams which conform to those most commonly used today are presented.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the technical guidance given by Dr. J. Lindsay of the Electrical Department, Concordia University, and that given by Dr. D. McGillis, of Hydro-Quebec.

Montréal, Quebec
November, 1978

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CHAPTER 1

INTRODUCTION

The present report is about various design methods which influence the design of transmission lines.

The voltage control problem associated with any a.c. transmission system has been greatly amplified with the introduction of extra-high-voltage networks. Analysis is performed to show the need for good voltage control in either the steady-state or transient conditions. In this report only the system aspect of voltage control is introduced. Permanently connected shunt reactors are needed to limit overvoltages due to load rejection and to absorb reactive power under light-load conditions. The switching of large capacitor banks or reactors into a network may not be sufficient to keep the system voltage within acceptable limits. For large variations of power, the two static devices can be replaced by a synchronous compensator which will help the lines to stay longer in service.

Many methods can be used to improve the operating characteristics of long transmission circuits. The most promising one is the line reactance compensation by means of series capacitors. The choice of switching arrangement depends on the relative advantages from the stability point of view.

Extra-high-voltage a.c. levels of 500 kV, 735 kV, are already in operation. The transmission capacity per line increases in slightly greater proportion than the square of the voltage, the optimum line loading being related to its surge impedance loading.

To improve the stability of a system it is more effective to use the methods as follows:

a) To install intermediate switching stations

b) To install synchronous compensators and static reactive compensators on the intermediate stations, and

c) by decreasing the line reactance using series capacitors and bundled conductors.

For the design of the extra-high-voltage system, analytical studies are performed using a digital computer, in order to get in consideration the best circuit. Important and careful consideration is given to the system performances, priority to the stability during and after different faults. The computer program tests for stability the 735 kV system with and without compensation. Also it tests the transmission line stability under severe conditions of an infinite bus as well as the transient stability for a three-phase bus fault and for a line-to-line fault on one circuit near the generation station.

In high voltage lines the principal electric stresses come from external overvoltages, for example, lightning. In the extra-high-voltage range the internal overvoltages (particularly switching-surge overvoltages) present the most difficult stresses to withstand. To withstand a given switching overvoltage the air clearances must be disproportionally increased, and more effective control is required. One way of reducing switching overvoltages is to insert closing resistors in the circuit breakers. Other ways considered are:

a) shunt compensation
b) relay protection
c) shunting of series capacitors, and
d) by using surge arresters.

The increased use of transmission lines over long distances, brings in many complications, such as voltage regulation, stability and line insulation. Bundle conductors are used at extra-high-voltage levels to minimize corona and radio interference. Corona is a cause of power loss as well as radio and television interference. Bundle conductors reduce line reactance, therefore increasing the capacity of the line. Its affects are on tower loadings, real losses and corona loss. Thermal capacity and losses are the main factors influencing the choice of conductors. The mechanical aspects of bundle conductors also influence the choice of conductor.

The experience of public utilities in the last decades has shown that the use of voltages in the extra-high-voltage range, creates new elctrical constrains in the choice of a conductor bundle. The normal solutions of these constraints have often degenerated into unacceptable mechanical burdens on the structures, thereby forcing the line designers to establish a much closer coordination between the electrical and mechanical aspects of transmission lines.

The adoption of bundled conductors introduced some mechanical disadvantages with respect to the equivalent single conductor. Line fittings are more complicated, ice loading is relatively higher and the dynamic behaviour of the bundle conductor, introduced another source of concern for mechanical engineers.

In this project, some of the more important factors entering into substation design and a few variety of substation single-line diagrams which conform to the most commonly used are presented. These lay-outs are for large out-door bulk power substations rated 115 kV and higher. Each of these arrangements must be carefully evaluated to determine its switchability for any particular location.

CHAPTER 2

VOLTAGE CONTROL

In the normal operation of a system, the power transmitted on a network varies with the load demand. This variation of power brings about voltage fluctuations caused by the variation of current through the line and transformer reactances. The voltage can be maintained within reasonable limits by well distributed reactive power sources, while the transformer taps and excitation system of the generators will automatically adjust to the new conditions. The reactive component of loads is supplied by reactive power sources, such as capacitor banks. These capacitor banks are installed as near the loads as possible.

The voltage control problem in an extra-high-voltage system is amplified by the fact that transmission lines are highly capacitive elements. During light-load conditions, that is, when the power transmitted is well below the surge impedance loading (SIL) of each line, a large amount of reactive power is produced, requiring the addition of shunt reactors. When the power transmitted is increased up to the surge impedance loading of each line it would be advantageous to remove these reactors in order to compensate the line reactive loss by the capacitive effects of the line.

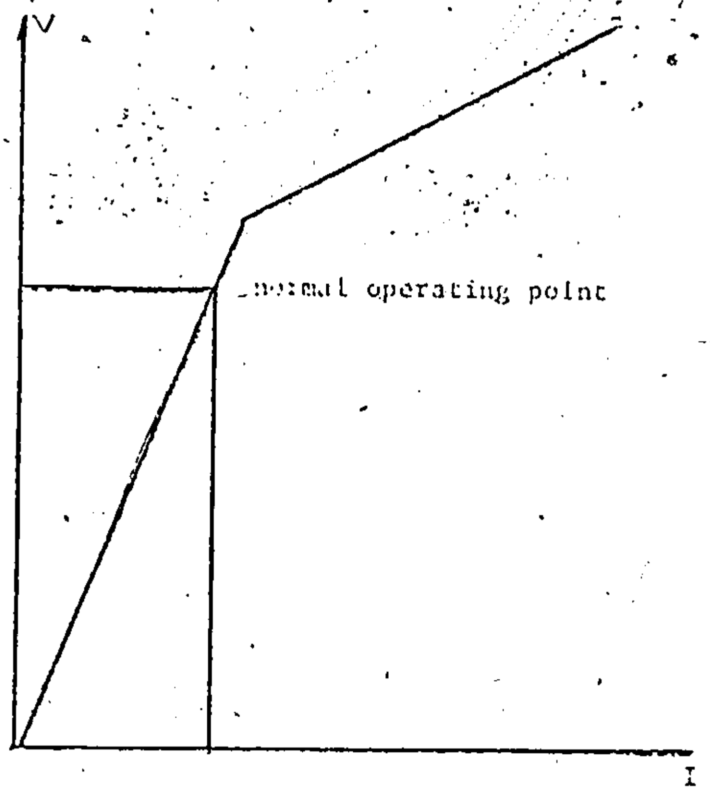
In the case of load rejection on an extra-high-voltage network, overvoltages occur and then permanently connected shunt reactors are needed to limit these overvoltages and to absorb reactive power under light-load conditions. System planners have to consider the ways to take full advantage of high-voltage transmission lines and limit the excessive overvoltages.

The use of saturable reactors that absorb very little reactive power at nominal voltage, seems to be a first step in the right direction, as shown in Fig. 2 [1].

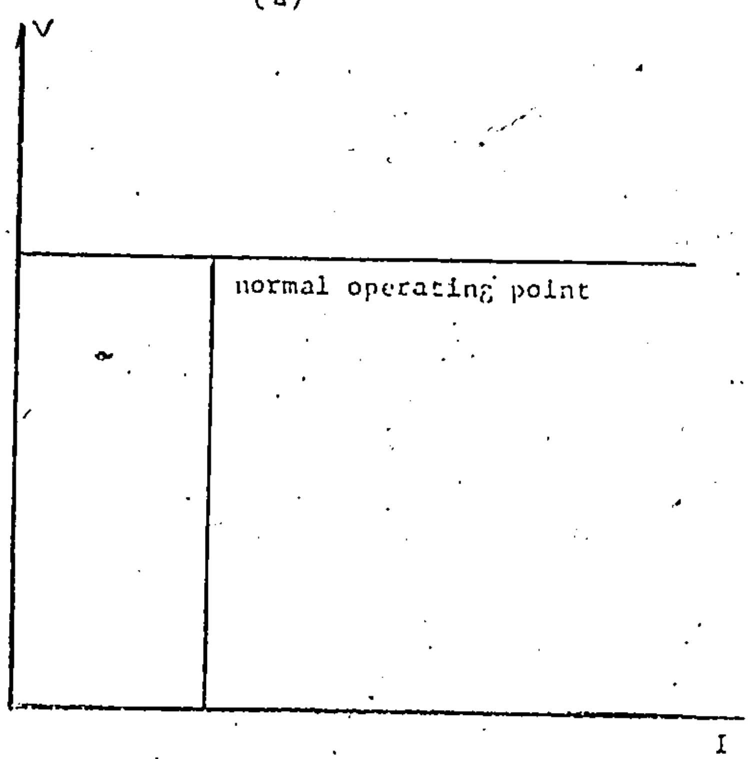
The switching of either capacitor banks or reactors, into a network, may not be sufficient to keep the system voltage within acceptable limits. In the case of large variation of power transmitted, line sections will have to be switched causing voltage fluctuations. These voltage fluctuations can be limited by using synchronous compensators which will help the lines to stay longer in service and would be possible to have an automatic system that would switch capacitors or reactor banks as directed by the absorption or production of reactive power by these compensators.

2.1 Transient Conditions

The braking torque electrically developed inside a generator when its rotor swings away from the average speed of the system can be resolved in two components. One is in phase with the speed error (first derivative of load angle variation) and is called the damping torque. The other is in time phase with the rotor load angle change and is called the synchronizing torque. Actually, most extra-high-voltage transmission systems have sufficient synchronizing torque to withstand a fault, but the loss of a line following the fault results in a big voltage problem. The loss of a line means the loss of a large amount of reactive power.



(a)



(b)

Fig. 2 — Voltage current characteristics of
a) an ideal saturable reactor
b) an ideal saturated reactor

Therefore, the main concern is to prevent a general voltage collapse after a severe disturbance. To stabilize a network the system voltage should be restored rather than to increase the synchronizing torque by adding more lines into the system.

Studies have been made for many years which show the effectiveness of good voltage control in an extra-high-voltage network. Hydro Quebec's first 735 kV system was composed of 3 lines from Manicougan to Montreal for the transmission of 5000 MW, as shown in Fig. 2.1 [2]. The generators are equipped with static excitation systems to maintain energy following a fault. With the advent of Churchill Falls, located some 640 km further than Manicougan, stabilizing signals were inserted in all machines at Manic-Outardes and Churchill Falls, so as to help damp out system oscillations.

It was evident that the loss of a line brought up voltage control problems. Synchronous compensators (voltage support) were added at both Montreal and Quebec City to help the operation of the system and also to produce reactive power following the loss of a line.

All the 735 kV lines were equipped with shunt reactors and the loading of these lines was below their surge-impedance loading. Recent studies have shown that a sixth line between Manicougan and Quebec City could be avoided if, following the loss of a line, the reactors on the adjacent lines were tripped out immediately following the clearance of the faulted line. The existing five lines have 330 Mvar reactors at each end and with an automatic device could switch out three reactors to keep the voltage at a high value to retain the stability of the system [2].

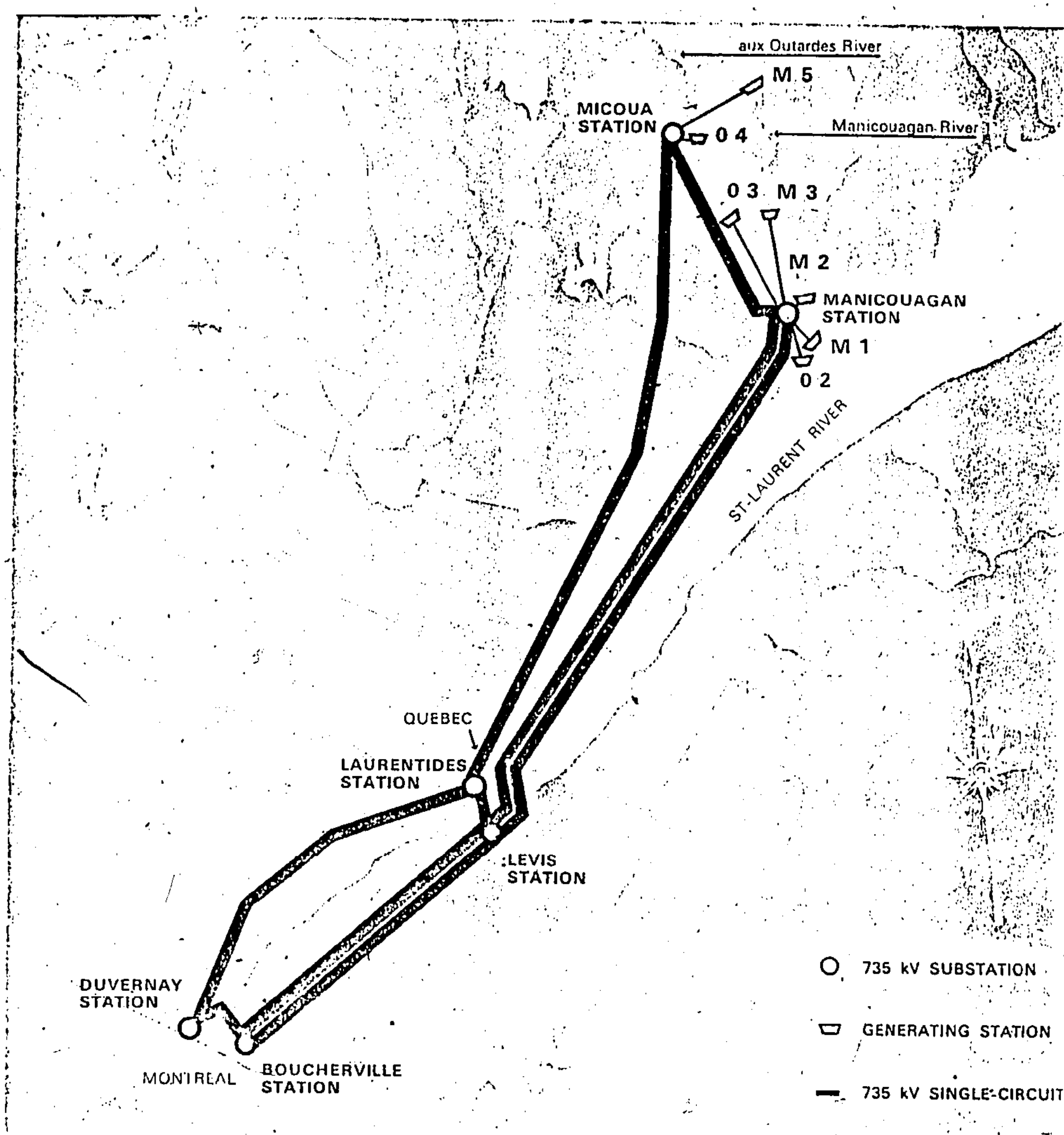


Fig. 2.1 — Hydro Quebec's 735 kV Transmission System.

Examining again the 735 kV project, ten lines would be needed to carry the 16 000 MW load transmitted from Rupert to Montreal and to maintain stability following the loss of a line. It has been shown that with good voltage control along the lines, the number of lines could be reduced to five. Also, economic studies have shown that the optimum number of lines is reached when each line is carrying approximately its own surge-impedance loading which in this case corresponds to seven lines [3]. Eventually, the shunt reactors must be switched out during peak conditions. To limit the temporary overvoltages due to load rejection, saturable reactors should be added to the system.

2.2 VOLTAGE SUPPORT EQUIPMENT

There are many ways to support the voltage of a system following the loss of a line. At the sending end static excitation systems with their fast response can hold the teminal bus voltage. Additional measures must be provided for the rest of the system. The most economical method is the switching of reactors or large capacitor banks.

The capacitor banks supply the reactive power needed and may be permanently connected to the system and switched on and off as the load demand changes. A synchronous compensator is capable of supplying reactive power equal to its rating to the system as well as absorbing it to an extent equal to 60% of its rating. For short periods, the synchronous compensator can supply reactive power in excess of its rating at normal voltage.

To switch fixed compensators or reactors in a system such as the Churchill Falls network would be sufficient. However, for a system where the lines are highly loaded and very long, such as the James Bay system, this simple operation would not be sufficient to stabilize the whole network. In this case, it is worth adding synchronous compensators which are equipped with static excitation systems, and can provide the necessary damping signal. The number of synchronous compensators needed depends on the loading of the lines and the length of these lines. The number of synchronous compensators can be reduced by switching in capacitor banks immediately following the loss of a line. However, too much reactive power switched to the system can underexcite the synchronous compensators and loose synchronism. It is possible to continue to reduce the number of synchronous compensators by adding capacitors in series. Compensation will have to be installed on the high side of transformers in order to reduce the short circuit currents.

A static shunt compensator used for voltage stabilization is shown in Fig. 2.2, consisting of a saturable reactor and an associated shunt capacitor together with a series capacitor. Also, Fig. 2.2 gives the voltage current characteristic of this device [4].

2.3 Maintaining System Voltage by Reactive Power Supply

The transmission of electric power over great distances has brought up stability problems to the network. There are at least two possibilities for achieving stable operation.

a) Series compensation to reduce the effective line length and thus strengthen the line, and

b) Shunt compensation to maintain voltage at selected intermediate points, in which case stable operation can be achieved under increased over-all phase angle.

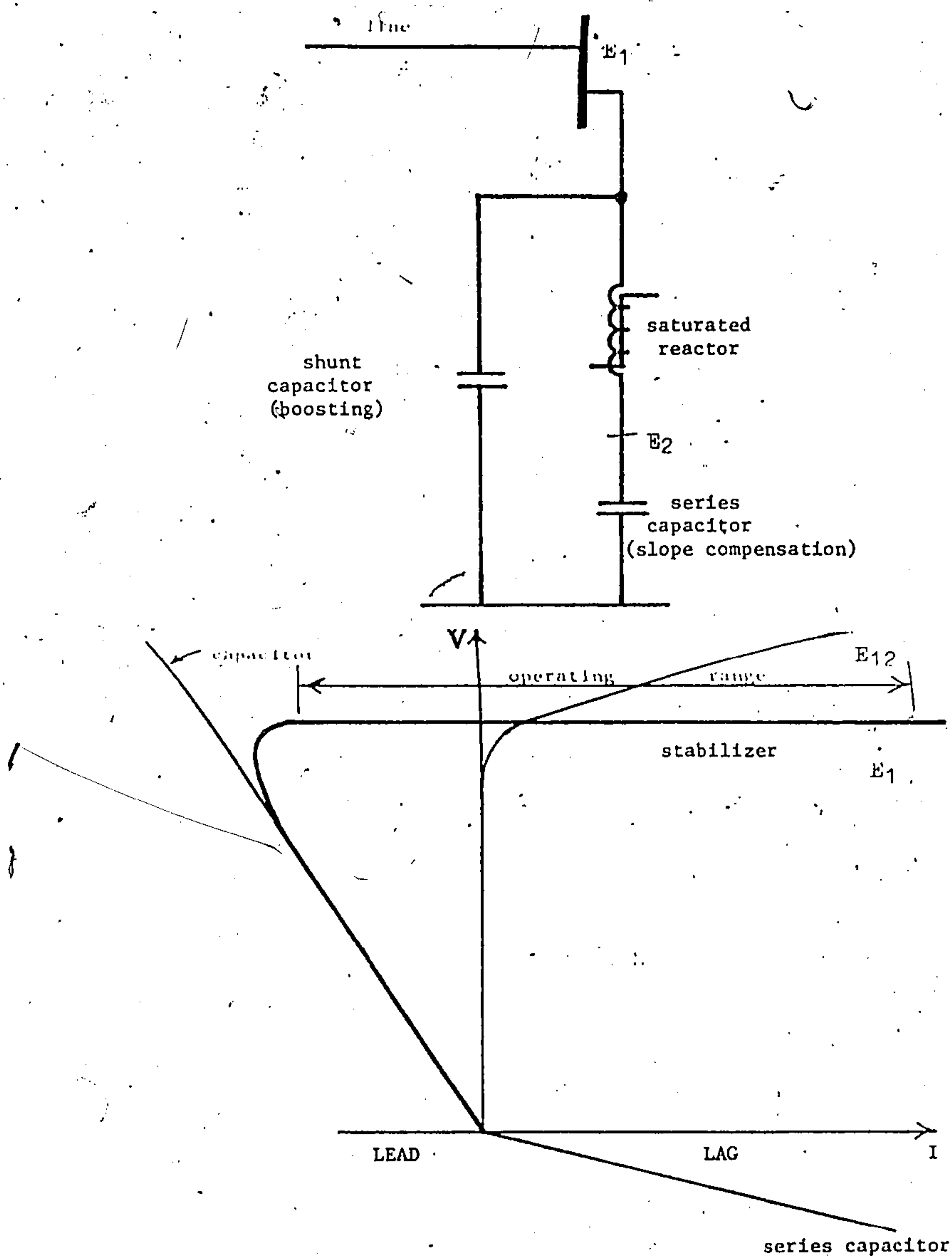


Fig. 2.2 — V-I Characteristic of Saturated Reactor and Shunt Stabilizer.

Shunt reactive-power compensation has received relatively little attention, as compared to series-capacitor compensation. Even the use of synchronous compensators for system voltage control tended to decline in favor of the more economical switched shunt capacitors [5].

The James Bay electrical power transmission project has given the opportunity for the system designers to choose and compare the performance and economy of shunt compensation, series compensation, and no compensation other than some fixed shunt reactors. Studies proved that shunt compensation is more favourable than other compensation.

In the normal steady-state condition the maintenance of good voltage at the load may require an additional controlled reactive-power supply, in view of the relatively small amount of generation locally available.

Static reactive-power compensators are essentially variable inductive reactors, the reactance being varied by controlled rectifiers. As stated previously, the synchronous compensator in steady-state operation has a range of reactive-power at its rating (+100%), to absorbing reactive-power at a value determined by its synchronous reactance (-60%), that is a range of 160%. To produce exactly this steady-state performance using a static compensator it is necessary to have a reactor that can absorb 160% reactive power together with a capacitor to supply 100% reactive power.

As far as the voltage regulation is concerned, in the case of the controlled reactor this is a question of the automatic voltage regulator used, just like the synchronous compensator. In the case of the saturating reactor, the voltage regulation will depend on the slope of the voltage versus the current characteristic of the saturated reactor, to which must be added the component of slope caused by the transformer used to connect the low-voltage reactor to the high-voltage transmission line. The total resultant slope would give a voltage regulation and it has been proposed to reduce this regulation by means of capacitors in series with the compensator [6].

When considering transient performance the characteristics of synchronous and static compensators are qualitatively different in several respects.

For severe voltage variations, the synchronous compensator may be more effective in keeping the voltage up, while the static compensator may be more effective in keeping the voltage down. This is only with respect to fundamental-frequency overvoltages. Transient voltages may be more severe with the static device because of the greater amount of shunt capacitance present.

With regard to the range, studies have shown that swings of reactive-power both above and below the initial value are required to maintain stability following a fault. Thus, any device must increase and decrease its reactive power output.

Further with regard to response, the synchronous compensator has a certain limited initial response as determined by its transient reactance, together with the transformer reactance. Its further response depends on the excitation control, which can be made very effective. The initial component of response can be increased by low transient reactance and even by the use of series capacitors, which have been shown to be very useful in improving stability.

The response of the static compensator with saturable reactor does not depend on control, but is entirely due to the inherent design.

CHAPTER 3

GENERAL CONCEPTS RELATED TO POWER SYSTEM DESIGN

The necessity for long-distance transmission of large blocks of power has grown rapidly during the last few years. Some of the large-scale hydroelectric developments in the western states are located in relatively remote areas and have given rise to transmission problems, involving distances of the order of 480 km and transmission of 15 000 MW of power [7].

The most important considerations in each major power development are:

a) The conservation and most effective utilization of important natural resources.

b) The delivery of large blocks of power to natural load centers at minimum annual costs.

c) The delivery of power to natural load centers with a high degree of reliability.

A basic analysis of the fundamental circuit properties involved, indicates that, although a number of methods can be used to improve the operating characteristics of long transmission circuits, the most promising one is the line-reactance compensation by means of series capacitors [8].

The 735 kV system with a certain number of lines, with and without compensation will be studied by a digital computer program. Also, the performance of such a system will be studied under the most severe conditions of an infinite bus in Montreal as well as the transient stability for a three-phase bus fault and for a line-to-line fault on one circuit near James Bay. A system to be stable must have some margin in the steady-state, that is, the initial angle should be such as to leave some room to move under the accelerating forces that are attendant upon the fault condition and also the restoring forces should be such as to bring the system back to the initial angle after the fault condition.

The power system design requirements are:

a) Power transmitted - 15 000 MW

b) Distance - 965 km

c) Load factor - 68%

d) Transmission voltage - 735 kV ac

Also, typical values for a 735 kV system may have the following conductor sizes:

735 kV 4-1361 MCM

Resistance $R = .010\ \Omega/km$

Inductive Reactance $X_L = .31\ \Omega/km$

Capacitive Reactance $X_c = 5 \times 10^{-6}\ \Omega/km$

3.1 THE REPRESENTATION OF A POWER SYSTEM AND ITS BASIC ANALYSIS

Reduced to its fundamental elements an ac transmission line and its associated transformers constitute a connecting link of finite impedance between a generating station and its load or between two electric systems. It has been shown that the power delivered over a circuit containing lumped impedance $Z \underline{/\theta^0}$ with voltages E_s and E_r maintained at the sending and receiving ends respectively, when these voltages are separated in phase position by the angle δ, is given by:

$$P_r = \frac{E_s E_r}{Z} \left[\cos(\delta-\theta) - \frac{E_r}{E_s} \cos\theta \right] \quad \ldots\ldots\ldots \quad 3.1$$

This equation was taken from the book of (William D. Stevenson Jr., 1975). [9]

If we neglect resistance which is very small in practical transmission circuits, then the power transmitted is given by:

$$P_r = \frac{E_s E_r}{X} \sin\delta \quad \ldots\ldots\ldots\ldots \quad (3.2)$$

The power transmitted is the product of the sending and receiving voltages and the angular displacement, divided by the total circuit equivalent reactance.

In general, a power system can be represented by a) generators b) transformers c) transmission lines, and c) the load.

3.2 Lossless Line

The representation of a long transmission line in terms of the distributed constants A, B, C, D, is given by the relation: [9]

$$\begin{bmatrix} E_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} E_r \\ I_r \end{bmatrix} \quad \ldots\ldots\ldots\ldots \quad 3.3$$

where:

$A = D = \cos h\gamma l$

$B = Z_0 \sin h\gamma l$

$C = \sin h\gamma l / Z_0$

where:

$Z_o = \sqrt{Z/Y}$, is the characteristic impedance of the line

Z = line impedance per unit length

Y = line admittance per unit length

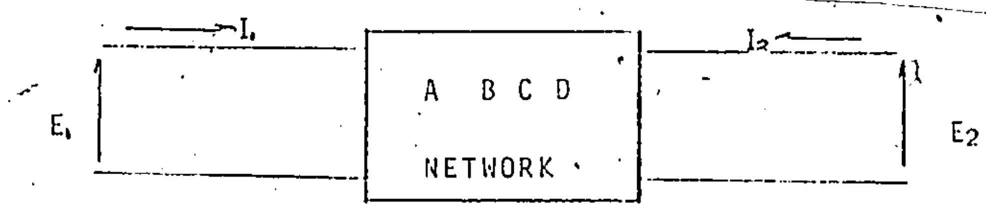
$\gamma = \sqrt{Y/Z}$, is the propagation constant

or $\gamma = a + jb$

where a = attenuation constant

b = phase constant

In general form the transmission system can be represented as a two port network, shown below:



In the case of a lossless line

$$Z_o = \sqrt{L/C} = \sqrt{X_c * X_L} \quad \ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

where:

L = line inductance

C = line capacitance

Also: $\gamma = j\omega\sqrt{LC} = jb$

$A = D = \cos bl$

$B = jZ_o \sin bl$

$C = j\, 1/Z_o \sin bl$

3.3 WAVE LENGTH

The wave length represented by the Greek letter, λ , is defined as the distance along the line between two points of a wave which differs in phase by 2Π radians. The wave length is given by:

$$\lambda = 2\Pi/b \quad km$$

where:
b = rad/km

3.4 SIL-SURGE IMPEDANCE LOADING

In power system work, characteristic impedance is called surge impedance (Z_0). The term surge impedance, however, is usually reserved for the special case of a lossless line. When dealing with high frequencies or with surges due to lighting, losses are often neglected and the surge impedance becomes important. Surge impedance loading (SIL) of a line is the power delivered by a line to a purely resistive load equal to its surge impedance [9]. In this case, the line supplies a current of:

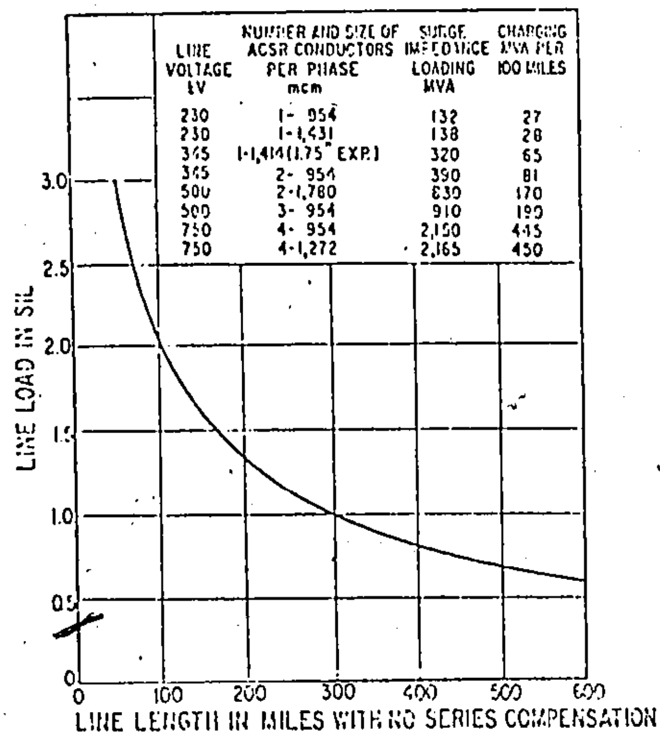
$$|I_L| = \frac{|V_L|}{\sqrt{3} * \sqrt{L/C}} \quad A \qquad \ldots\ldots\ldots\ldots (3.5)$$

where: $|V_L|$ is the line to line voltage at the load

$$SIL = \sqrt{3}\,|V_L|\frac{|V_L|}{\sqrt{3} * \sqrt{L/C}} \quad W$$

$$\text{or} \quad SIL = \frac{|V_L|^2}{\sqrt{L/C}} \quad W \qquad \ldots\ldots\ldots\ldots (3.6)$$

The curve of fig. 3.4 was taken from the national power survey report [10], and is representative of practice with respect to per unit surge-impedance loading of uncompensated lines as a function of line length.



LINE VOLTAGE kV	NUMBER AND SIZE OF ACSR CONDUCTORS PER PHASE mcm	SURGE IMPEDANCE LOADING MVA	CHARGING MVA PER 100 MILES
230	1- 954	132	27
230	1-1,431	138	28
345	1-1,414 (1.75" EXP.)	320	65
345	2- 954	390	81
500	2-1,780	830	170
500	3- 954	910	190
750	4- 954	2,150	445
750	4-1,272	2,165	450

Fig. 3.4 — Transmission Line Capability in Terms of Surge-Impedance Loading.

In the range of 500 to 1500 kV, assuming bundles of 4 to 8 conductors per phase, the surge impedance is nearly constant at 260 ohms and SIL is practically proportional to the square of the system voltage. On this basis the following relationship is established:

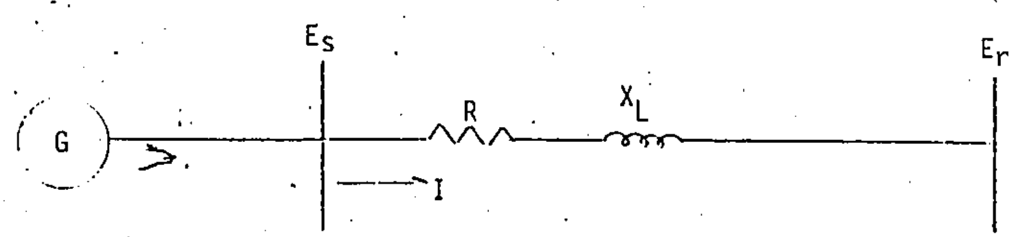
Volume, kV	SIL, MW
500	1000
750	2000
1100	4500

CHAPTER 4

SERIES CAPACITORS FUNDAMENTALS

Series unit capacitors have application on transmission lines. Behavior of the shunt capacitor is generally well understood. The same is not always true of the series type. Many questions are still unanswered and many problems are still unsolved [11].

From the construction point of view, shunt and series capacitors are the same. In fact, should the need for a series capacitor disappear, the capacitor units can be removed and reinstalled as shunt units. The two types differ in their method of connection. The shunt unit is connected in parallel across full line voltage. The series unit is connected in series in the circuit and hence conducts full line current. The voltage drop across the series capacitor changes instantaneously with load. The series capacitor introduces negative or leading reactance. Current through this negative reactance causes a voltage drop that lags the current by 90 degrees, and this drop is opposite from that across the inductive reactance. Thus, a series capacitor compensates for the drop, or part of the drop through an inductive reactance of a feeder. A feeder circuit is represented as follows:

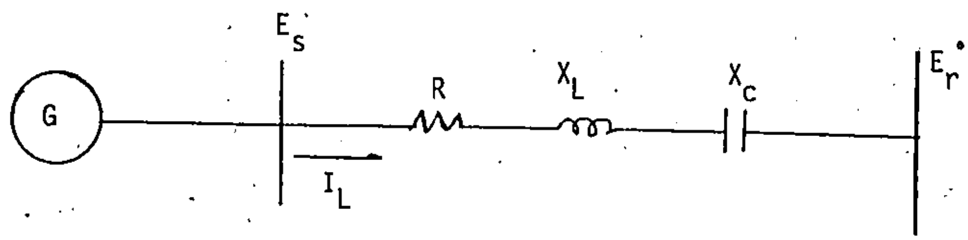


The difference between the sending and receiving voltages for this circuit is:

$$\Delta V_1 = IR\cos\theta + IX_L\sin\theta \quad \ldots\ldots\ldots\ldots 4.1$$

where θ = phase angle

In the case of a line having a series capacitor the circuit will be as follows:



The voltage difference will be:

$$\Delta V_2 = I_L R\cos\theta + I_L(X_L - X_c)\sin\theta \quad \ldots\ldots\ldots\ldots 4.2$$

or

$$\Delta V_2 = I_L R\cos\theta \text{ when } X_L = X_c$$

or

$$\Delta V_2 = I_L R\cos\theta - I_L(X_L - X_C)\sin\theta \text{ when } X_C > X_L$$

4.1 Size and Location of Series Capacitors

The size of series capacitors introduced in a power system depends on:

a) maximum load

b) future growth of load

c) amount of voltage improvement desired

d) reactance of line and transformer banks involved.

The size of capacitor (Mvar) = $3 * V_C * I_L^2 = 3 * I_L^2 * X_C$ 4.3

where I_L = load current (line current)

ΔV_C = voltage drop across the capacitor

As far as location is concerned these can be located at any point in a single-circuit line but preferably near the reactance center of the system. This will limit the duty on the capacitor protective equipment, reduce the voltage to the ground and minimize the problems of existing-inrush currents [11].

In case of multiple-circuit lines the series capacitors can be located in the individual line sections or in the common-bus connections.

Multiple-circuit lines are normally laid out so that the circuit load can be carried with one line section out of service. For such conditions there is a decided advantage in using the series capacitor in a common bus connection, not only because the capacitor kvar is not reduced by the switching out of a line section, but also because fewer units are required.

4.2 Switching Arrangements for Series Capacitors

Series capacitance may be required for the condition of highest circuit reactance but may not be needed for the normal condition with all lines in service. Hence, series capacitance can be used in two ways:

a) Series capacitors normally in the circuit, shunted for the fault condition, and quickly restored to the circuit after fault isolation

b) Series capacitors not normally in the circuit, but switched into the circuit after a line section is switched out of service.

The choice between these arrangements depends upon the relative advantages from the stability point of view.

4.3 Amount of Compensation

Stability and economic conditions control the amount of capacitive reactance to be used in any particular case.

The amount of compensation is the ratio in percent, of the capacitive reactance to the total reactance withall line sections in service. The amount of compensation can increase the stability limit for both transient and steady-state operation. The steady-state stability limit of a system without loss occurs at the angle of 90^0 between sending and receiving ends. The steady-state limit for a three-phase system is given by:

$$P_{max} = \frac{E_r E_s}{X} \sin\theta \quad \text{at} \quad \theta = 90^0 \quad \ldots\ldots\ldots\ldots (4.4)$$

This steady-state stability limit can be achieved by line reactance compensation while θ can be smaller than 90^0. The same holds true for the transient stability case but in addition define the conditions under which transient-stability limit applies. For example, for the switching operation the transient limit depends upon the stability limit for the final circuit conditions and upon initial operating angle.

Chapter 5

Power System Behaviour From Stability Standpoint

Stability is a measure of the ability of the system to overcome the accelerating forces that develop in the system from time to time.

In its broadest sense, power system stability is that property of a power system which ensures that it will remain in operating equilibrium (synchronism) through normal and abnormal conditions. Any power system must have a certain degree of stability in order to operate well. The object of engineering analysis, therefore, is the determination of the stability margin that a power system has for a given set of operating conditions or contingencies. If, for a given contingency the power system cannot remain in operating equilibrium, the system is called unstable for that contingency, otherwise it is called stable.

The terms stable and unstable can be used only in the context of a particular contingency or disturbance, to which the system may be subjected. A system may be stable for one set of contingencies and unstable for another more stringent set of contingencies. Because of this, the selection of an appropriate set of contingencies for which stability of a given power system should be tested, constitutes a vital step in system stability analysis.

For the purpose of identification, the total aggregate of operating conditions or contingencies for which a power system may be tested for stability can be classified into three broad categories, or "states of stability", namely:

a) steady-state, encompassing all operating conditions characterized by slow and gradual changes.

b) transient-state, encompassing all operating conditions characterized by sudden changes in load or circuit conditions and

c) dynamic-state.

Accordingly, the term steady-state stability refers to stability of a power system under operating conditions classified as falling within the "steady-state" category, while the term transient-state stability, or simply transient stability, refers to stability of a power system under operating conditions, classified as falling within the "transient-state" category. Dynamic stability may also be considered as a subclassification of steady-state since it is more properly called dynamic steady-state stability. It is used in the technical literature in reference to steady-state conditions when automatic regularity devices, such as automatic voltage regulators on the generators and the automatic speed governors on the turbines, play a particularly crucial role in affecting stability performance of a power system.

Since in the actual, physical performance of a power system there is no precise delineation between the steady-state, transient state, and dynamic state of operation, the concept of overall power system stability is often most appropriate in discussing the stability characteristics of a power system. It emphasizes the fact that any major system disturbance usually involves the transition in the system's performance from steady-state (prior to the disturbance), through transient state (immediately after the disturbance , when automatic regulating devices of the system are not yet effective), through dynamic state (when the action of automatic regulating device, affects the performance of the system in its reaction to the original disturbance), and finally back into a steady-state (post-disturbance) operating mode.

While in the discussion that follows, the steady-state, transient, and dynamic stability characteristics of a power system will be reviewed separately for the sake of clarity, it needs to be kept in mind that when considering the reliability of bulk power supply they all are part of the same broad concept which relates to the ability of the system to ride successfully through a disturbance whether sudden or gradual.

5.1 STEADY-STATE STABILITY

Steady-state stability is the ability of the system to remain in synchronism following a gradual or relatively slow change in the amount of power being carried through its transmission network. This is illustrated in Fig. 5.1 which shows examples of stable and unstable steady-state behaviour of a synchronous machine, in terms of the osciallations of its rotor in relation to the synchronously rotating electrical reference frame following a small increase in prime-mover power input [12].

The steady-state stability of a power system depends (as does the transient and dynamic stability) on the characteristics of all the basic elements of the system, namely, generators, system load, and the transmission network, tying together generation and load, as well as on the presence and effectiveness of automatic control devices. The two by

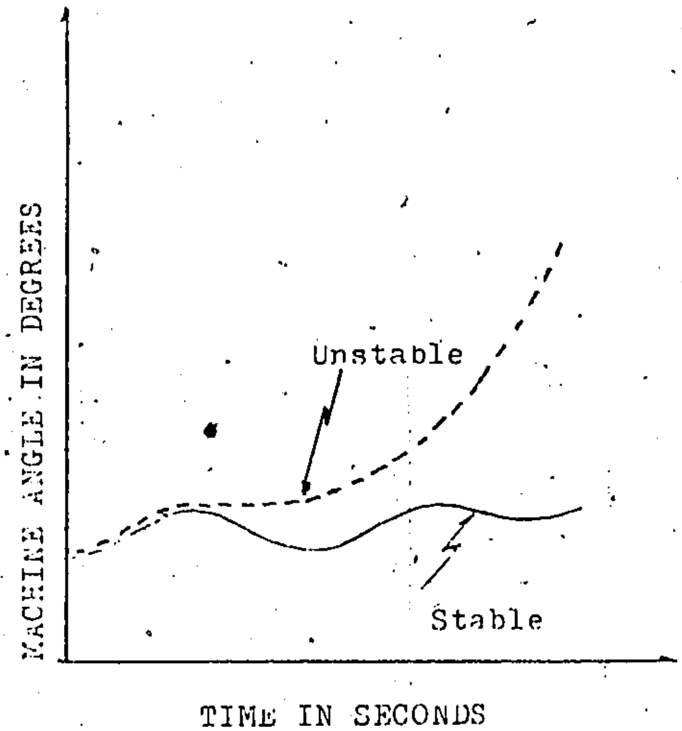


Fig. 5.1 — Example of Steady-State Behaviour of a Synchronous Machine Following a Small Increase in Prime-Mover Power at Constant Excitation Voltage.

far most important factors contributing to steady-state stability are, a strong transmission system and the presence of modern continuously acting automatic voltage regulators on the generators.

On modern power systems, steady-state stability (in its nondynamic domain) rarely constitutes a limiting factor, since the requirements associated with transient and dynamic stability would ordinarily assure adequate steady-state stability margins.

5.2 TRANSIENT STABILITY

Transient stability refers to the ability of the system to remain in synchronism (prior to the action of automatic speed governor control) following a system disturbance, involving one or more of the following:

a) a sudden, substantial increase or decrease in the amount of power supplied to the system (as, for example, following a sudden loss of a large generating unit or power plant).

b) a sudden, substantial increase or decrease in the amount of power consumed on the system (as for example, following a sudden loss of a large industrial load, or an entire major load center).

c) a sudden change in the ability of the transmission network to carry power (as for example, during a short circuit on one of the transmission lines, followed by tripping of the affected line). This is illustrated in Fig. 5.2, which shows an example of the stable and unstable transient behaviour of a synchronous machine, in terms of the oscillation of its rotor in relation to the synchronously rotating electrical reference frame, following a sudden disturbance.[12].

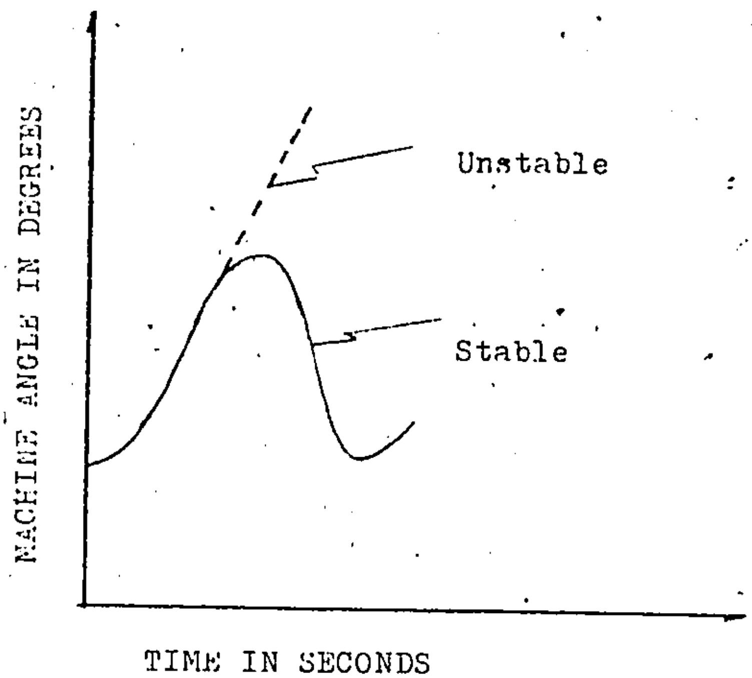


Fig. 5.2 — Example of Transient State Behaviours of a Synchronous Machine Following a Sudden Disturbance.

Major factors affecting transient stability of a power system include:

a) The stength of the transmission network tying together the generating sources and load centers of the system, as well as tying the power system to its neighbouring systems.

b) The characteristics of the generating units in terms of their mechanical properties, such as the inertia of the turbo-generators, and their electrical properties, such as transient reactances and magnetic saturation characteristics of the synchronous machines.

c) The speed with which faulty pieces of equipment, in case of a short circuit, can be isolated from the rest of the system by circuit breaker action and then, after removal of the short circuit, can be restored to service.

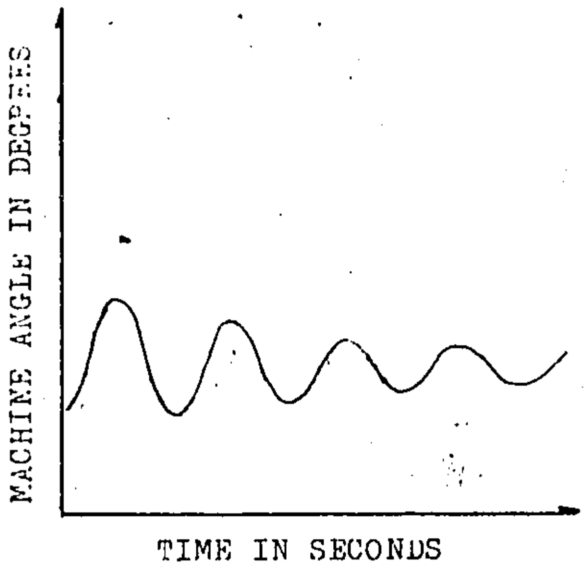
d) The speed with which the excitation system and the automatic voltage regulating equipment of the generating units can respond to a system disturbance involving reduction in system voltages and can act toward restoration of adequate voltage levels.

The time required for the first swing during the oscillation of a synchronous machine, following a sudden system disturbance, depends on the characteristics of the turbo-generators and of the transmission network. In most cases, this takes place within the first second of the disturbance. This is about the period of time during which the automatic speed governor control is not yet effective and the assumptions of transient stability analysis are rigorously applicable. After the "first swing" period, the effect of automatic speed-governor control needs to be taken into account and the phenomenon enters the domain of dynamic stability.

5.3 DYNAMIC STABILITY

Dynamic stability refers to the ability of the power system to remain in synchronism after the "initial swing" of the rotors and until the system has found a new steady-state equilibrium. The period of dynamic stability begins at about 1 to 1 1/2 seconds following the disturbance, when the automatic speed-governor control begins to change the turbine power input to the generators, and continues until a new condition of steady-state equilibrium has been reached at about 10 seconds to 30 seconds following the initial disturbance. This also includes the period during which the tie-line power frequency control operates to change the settings on the speed-governor control of the individual generators in an effort to restore the scheduled tie-line power flow and frequency. [13]

An example of dynamically stable and dynamically unstable behaviour of a synchronous machine following a sudden system disturbance, is shown in Fig. 5.3. The top figure illustrates the condition of dynamically stable behaviour of a synchronous machine following a disturbance. The bottom figure shows the condition when the machine is transiently stable but dynamically unstable. Also, it shows the oscillatory character of dynamic instability in which the voltage, current and angle of a synchronous machine develops oscillations which grow in magnitude until an "out-of-step" condition takes place. The oscillations generally occur with an interval of time between consecutive crests from less than a second to several seconds, depending on the strength of the electrical ties between machines relative to the inertia of these machines. Oscillations with intervals up to 10 seconds between crests can occur between groups of machines; or between major power systems connected by relatively weak transmission ties. The possibility of dynamic instability following a disturbance



Example of Dynamically Stable Behaviour of a Synchronous Machine Following a Disturbance.

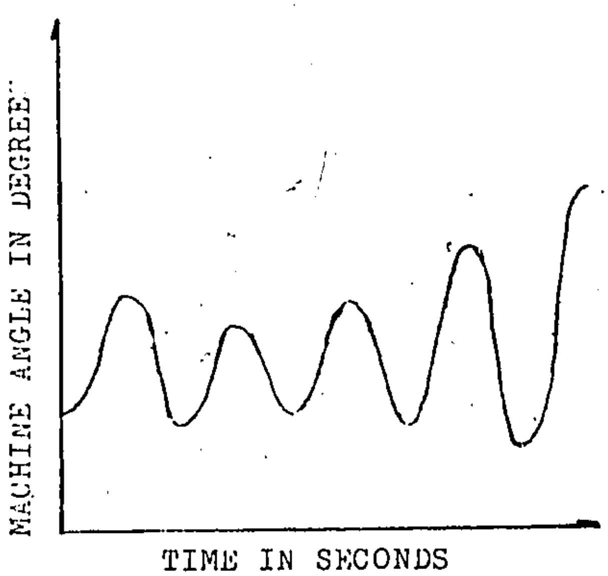


Fig. 5.3 — Example of Transiently Stable but Dynamically Unstable Behaviour of a Synchronous Machine Following a Disturbance.

makes it essential to check the stability performance of a power system behind the "first swing" in all critical cases.

5.4 Improvement of Stability

For the 735 kV transmission line system all power generated is many kilometers away from the load. In this case, the transmission system must be based on stability considerations.

As far as the steady-state stability limit is concerned, the total angular spread between the internal voltages of the sending end and the receiving end should be close to 90^o. This means that the angular spread across the transmission system should be the difference between 90^o and the sum of the voltage angles across the equivalent machine reactances at both ends of the transmission line system. The phase angle between the ends of the line should normally be around 30^o for stability reasons. Fig. 5.4 shows transmission line capability in terms of 30^o angular spread. [14]

There are many methods to improve stability. The most effective ones are as follows:

a) To install intermediate switching stations in the case of two or more lines in parallel in order to limit the length of the section of the line and tripping out quickly in the case of line fault.

b) To install synchronous compensators and static reactive compensators at the intermediate stations in order to support the voltage when reactive power is injected into the system during and after the fault.

c) By decreasing the line reactance using series capacitors and bundled conductors.

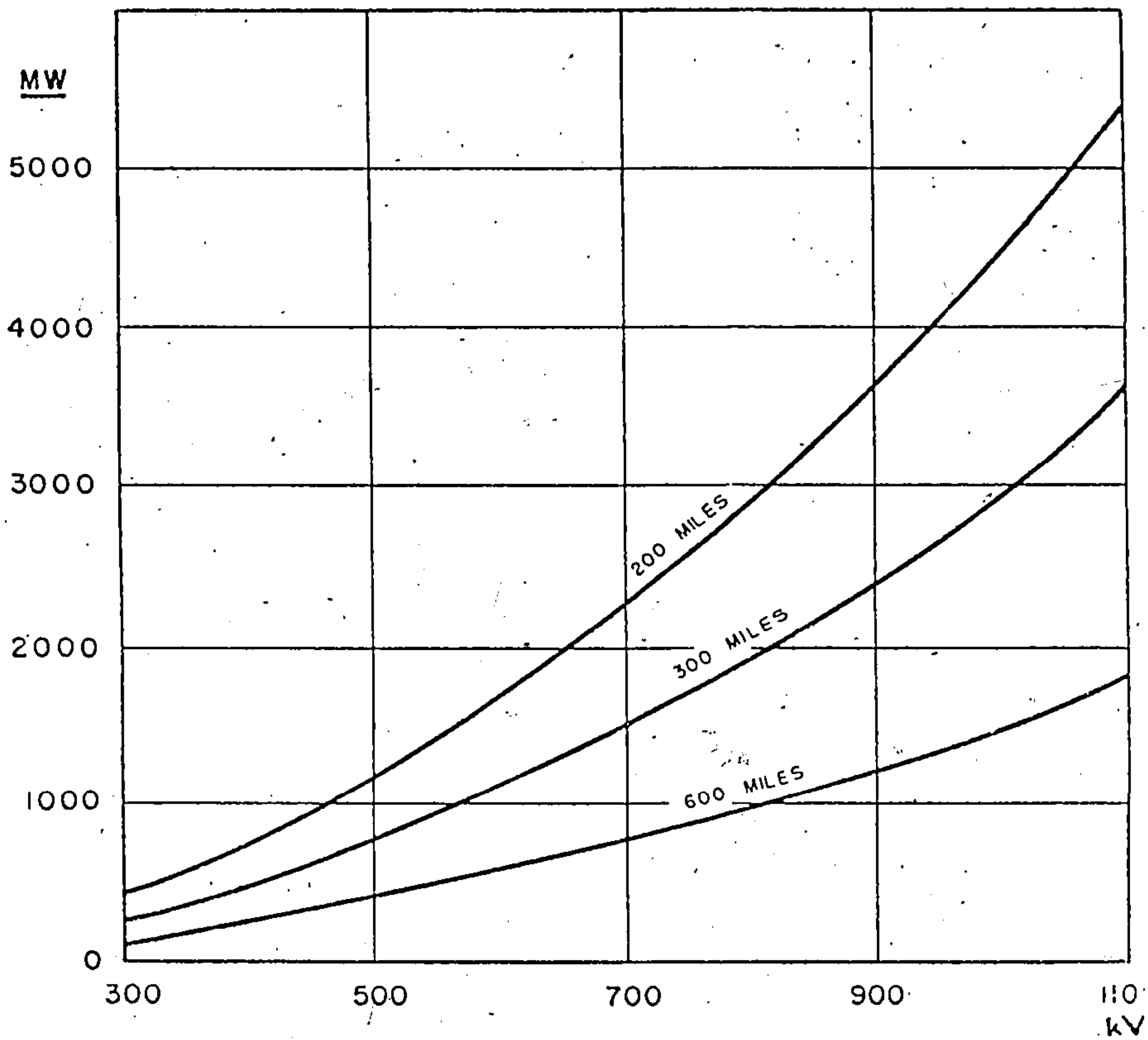


Fig. 5.4 — Transmission Line Capability in Terms of 30° Angular Spread.

5.5 Power System Stability with Series Capacitors

Series capacitors increase the stability limits of power systems by reducing the series or transfer reactance between internal voltages of machines, consequently increasing the synchronizing power [15]. Usually the transient-stability limits are well below the steady-state limits, so that an increase in the former is possible before the latter condition becomes controlling.

A physical picture of the system phenomena during a fault and the resulting transient can be obtained from Fig. 5.5.

The electrical power system is assumed to consist of a hydroelectric generator feeding through a series-capacitor transmission system to an infinite bus, subjected to a fault at point F which is cleared by the isolation of the faulted line section. The circuit is assumed to be without loss, so that the power angle diagrams are simple sine curves. The curves on Fig. 5.5 show four conditions:

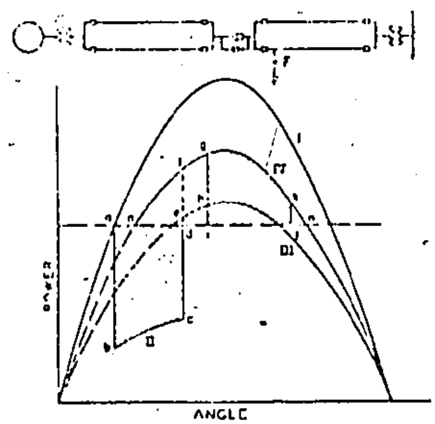
a) The initial condition with all lines and series capacitors in service, curve I.

b) Condition (a), plus the application of the fault and the shunting of the series capacitors, curve II.

c) Normal condition, but with one line section and series capacitor out of service, curve III.

d) The system normal with series capacitors in circuit but with line section out of service, curve IV.

Consider the system of Fig. 5.5, operating at the load and angle corresponding to point a on curve I. Upon the application of the fault,



ab - Fault on one line section, series capacitor shunted
ce - Faulted line section switched out
hg - Series capacitor restored to the circuit
k - Point of maximum angular swing
For stability,

$$\text{area }(abcd) \leqq [\text{area }(edh) + \text{area }(gjk)]$$

Curve	Fault Condition	Capacitor	Line Sections Out
I	Before	In	None
II	During	Out	None
III	After	Out	One
IV	After	In	One

Fig. 5.5 — *Power-Angle Diagram for Sending End of Series-Capacitor Transmission System Connected to Infinite Receiver.*

the output of the generator drops to the point b on curve II. The difference in power ab accelerates the generator and increases the angle by which it leads the receiver. At the point c the fault is to be isolated by the action of high-speed breakers and relays, thus changing the operating point to e on curve III. Power corresponding to de decelerates the generator but because of the inertia it swings forward along curve III. At the point h the series capacitor is restored to the circuit, by the opening of the shunting path in the protected equipment, and operation proceeds from the point g on curve IV. Because the energy stored during the acceleration period, has not been completely absorbed, the system continues to swing forward to point k, such that the decelerating area [area (edih) + (gijk)] equals the accelerating area (abcd). Considering this, stability occurs when, area (abcd) $\leq$ (edih + gijk) area. The system would be unstable for the conditions shown unless the series capacitors were restored to the circuit fast enough after the isolation of the faulted line section.

It is important to use high-speed breakers and relays for circuit isolation when series capacitors are used. Also, the duration of the fault, is of greater importance than the duration of the period in which the series capacitor is shunted by protective equipment.

The power-angle curve II of fig. 5.5 is based on faults of the low-resistance type. If the system faults are of the high resistance type, such as may occur on lines without ground wires, the resultant load on the generating station may be greater than the normal output. Under such conditions the power-angle diagram is different than that of Fig. 5.5 in the aspect of having curve II above curve IV, because at the instant of the fault the output of the generator increases [15].

5.6 DIGITAL COMPUTER PROGRAM FOR DETERMINING STABILITY

Many sophisticated programs are available for determining the stability of large power systems. In this project-report, a simple digital computer program has been formulated and utilizes Fortran. The program tests sectionalized lines for stability under various faults, with and without compensation. Details of the results are shown in the appendix.

The program is based on standard expressions that are found in most references [9]. A summary of the system dynamics involved follows.

The accelerating power, $P_a = P_m - P_e = m_a$

where: P_m = mechanical power

P_e = electrical power

Also $$P_e = \frac{E_s E_r}{x} \sin\delta \quad \text{. . . . . (5.1)}$$

or $$P_m = \frac{E_s E_r}{x} \sin\delta = 1$$

$$\therefore \; P_a = 1 - \frac{E_s E_r}{x} \sin\delta = ma = m\frac{\partial}{\partial t^2} = \frac{H}{\Pi f}\frac{\partial^2\delta}{\partial t^2}$$

H is chosen to have physical significance.

$$\therefore \; 1 - K_1 \sin\delta = K_2 \frac{\partial^2\delta}{\partial t^2}, \qquad K_1 = \frac{E_s E_r}{x}$$

The above differential equation has no analytical solution, thus a step-by-step solution is performed.

$$\therefore \; \Delta\delta = \Delta\delta_{n-1} + P_a(n-1)\, 180f \frac{(\Delta t^2)}{H} \quad \text{. . . . . (5.2)}$$

For t = .05 sec, and H = 3 for Hydro case.

Then $180\, f\, \frac{(\Delta t)^2}{H} = 9$

$$\therefore \quad \delta_n = \delta_{n-1} + \Delta\delta_n$$

$$\Delta\delta_n = \Delta\delta_{n-1} + 9P_{a(n-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

The flow chart of the computer program is shown in Fig. 5.6.

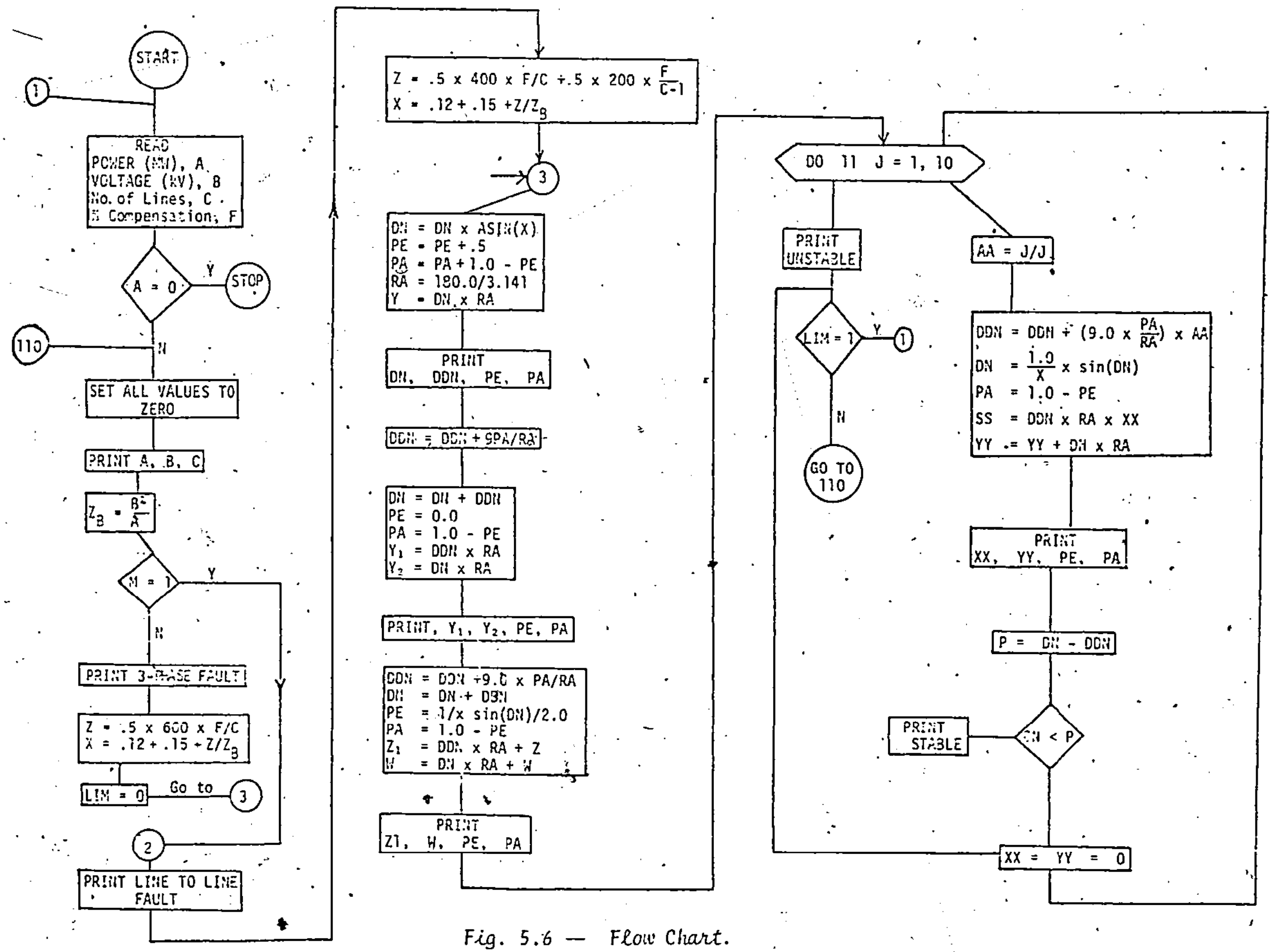


Fig. 5.6 — Flow Chart.

CHAPTER 6

DIELECTRIC STRENGTH OF AIR INSULATION TO 735 kV SYSTEM

With the transmission of 15 000 MW of power over a distance of 644 km at the 735 kV voltage level, the cost of the transmission is affected by the insulation of the line against overvoltages.

The transmission line insulation brings about two problems:

a) The voltage stresses which the insulation must withstand, and

b) The response of the insulation when submitted to these stresses. The affect of voltage stresses is shown on Table 6.

The insulation coordination is the balance between the electric stresses on the insulation and the dielectric strength [16]. The voltage stresses on transmission lines insulation are formed from the various overvoltages. With normal operating voltage the insulation is not affected, but under polluted conditions, for example, it affects the insulation. Also the power frequency voltage determines the insulation strength of the line. The line insulation level determines the insulation string length and other spacings which affect the size of the towers and the width of the line route. The normal operating voltage determines the conductor size which affects the tower size because of the corresponding mechanical loading stresses.

In general, as the operating voltage increases, the power transfer increases and higher resulting switching surge overvoltages occur. The overvoltages stressing a power system may be either external or internal and must be limited as far as possible [17].

6.1 EXTERNAL OVERVOLTAGES

External overvoltages are generally generated by atmospheric disturbances and often are called atmospheric overvoltages. The most common atmospheric disturbance which can generate an overvoltage is lightning among other less important external phenomena. The stresses on the insulation caused by lightning do not entirely depend on the voltage of the power transmission line system. Actually, the stresses produced by lightning decrease relatively as the operating voltage increases. This means that external insulation is not subject to severe stresses, which does not hold true for the internal insulation.

Therefore, in the case of a 735 kV system, lightning no longer represents a severe stress for external insulation [18].

6.2 INTERNAL OVERVOLTAGES

The 735 kV system insulation is subject to internal overvoltages. These internal overvoltages are mostly generated by change in the operating conditions of the network, such as, a switching operation, a fault, or a sudden change in load. Furthermore, internal overvoltages are subdivided into a) switching, and b) temporary overvoltages.

a) Switching overvoltages are generally of an oscillatory nature and are caused by switching operations such as energizing and de-energizing of a line, fault application, fault clearing, and load rejection. A switching surge overvoltage is a rapid transient condition duration of a few microseconds, composed of oscillations, one of which has the maximum amplitude and constitutes the critical stress for the insulation. When referring to switching overvoltages only the maximum in amplitude of an oscillation is considered.

Switching overvoltages can be formed by a single unidirectional impulse of irregular shape with a time-to-crest of a few hundred microseconds and a half amplitude time of similar magnitude.

In Hydro Quebec's laboratory, tests are made under various switching surges, and it has been observed that under usual switching surges the breakdown of air gaps occurs before the crest of the impulse. This means that the front is the only significant part of the impulse, as far as the insulation response is concerned.

b) Temporary overvoltages, are an oscillatory phase-to-ground or phase-to-phase overvoltage of long duration at a given location. It is undamped or only lightly damped in contrast to switching and lightning overvoltages, which are usually highly damped and of short duration. These oscillatory temporary overvoltages up to 735 kV do not represent a severe stress for air insulation. Their importance influences the choice of the surge arresters and therefore the internal insulation of station equipment.

Overvoltage phenomena occuring in power systems must be classified as temporary overvoltages. The ones that are pertinent to insulation of extra-high-voltage systems and have a direct bearing on the selection or performance of surge arresters can be classified into three groups:

a) Temporary overvoltages with a frequency of oscillation higher than power frequency, due to forced higher harmonic oscillations. These are caused by steady-state resonance due to the non-linear magnetizing inductance of the power transformer or by transient resonance due to the switching operation of the power transformer.

b) Temporary overvoltages with a frequency of oscillation much lower than power frequency, due to forced subharmonic oscillations. These are caused, for example, by the clearing of a fault with series compensation.

c) Temporary overvoltages with a frequency of oscillation at or near power frequency. These may be caused by loss of load or energization of an open line.

6.3 EFFECTIVE MEANS OF CONTROLLING THE INTERNAL OVERVOLTAGES

In the case of a sudden loss of load of a transmission line, temporary overvoltages occur. These overvoltages can be reduced by the installation of shunt reactors at suitable locations along the transmission line. The shunt reactors compensate the capacitive charge of the line. Shunt reacotrs normally have fixed values, but saturable reactors can achieve better compensation in that they can respond to changes in load [1].

In the extra-high-voltage range, switching overvoltages are caused by the closing or reclosing of a line. These overvoltages can be reduced by the temporary insertion of closing resistors in the circuit breaker. These resistors reduce the initial value of the step voltage applied to the line at the moment the contacts close. Proper choice of the magnitude and of the time of insertion of the resistors results in a reduction of line energization overvoltages. [19].

Also, switching overvoltages can be generated by instantaneous reclosing of a line, due to the trapped charge voltage. This trapped charge voltage is added to the energization voltage giving a higher overvoltage. There are many ways of controlling the additional overvoltage due to the trapped charge. It has been shown [19] that it is possible to limit switching-surge overvoltages on reclosure and trapped charge, using closing resistors, as mentioned before [19].

Other ways of controlling overvoltages are:

a) by installation of shunt compensation and proper relaying

b) by relay protection system

c) by shunting the series capacitor by a circuit breaker

d) by using surge-arresters.

6.4 Dielectric Strength of External Insulation

Air insulation under switching impulses has the characteristic that the breakdown voltage as a function of the clearance of the gap saturates which means that the mean breakdown gradient decreases as the gap increases [20]. To withstand a given switching overvoltage the air clearances must be disproportionally increased. In this case more effective control is required as the operating voltage increases. It has been shown that the 50% positive, slow-front impulse breakdown voltage of the air insulation of an air gap depends on the time-to-crest of the impulse [21]. There exists a critical front for which the insulation breaks down under a minimum voltage. For a time-to-crest above or below the critical front the conductor-to-tower air-gap shows a higher breakdown strength. Fig. 6.4 shows a family of V-shaped curves with 50% breakdown voltage characteristics as a function of the time-to-crest for various tower window models. These curves were obtained from test at the Hydro-Quebec Research Institute [22].

6.5 Transmission Line Insulation Design

The transmission line insulation system has the function of isolating the conductors from the ground and insulating them from the tower.

In the design of extra-high-voltage systems the switching surge is the main factor for determining the external insulation and the line insulation level. This in turn determines the insulator string length and other spacings that again affect the dimensions of towers as well as the width of the line.

The conductor size is dependent on normal operating voltage and power transmitted. This, in turn, affects the tower dimension in respect to certain mechanical loading stresses.

During the past years there have been considerable advances in the approach to transmission line insulation design [23]. The use of analog and digital techniques for the determination of the switching overvoltages has improved tremendously. Table 6 shows the effect of the three types of voltage stresses on the line insulation characteristics [23]. Up to 362 kV lightning is the determining stress after which the switching surge takes over and determines the clearance. However,

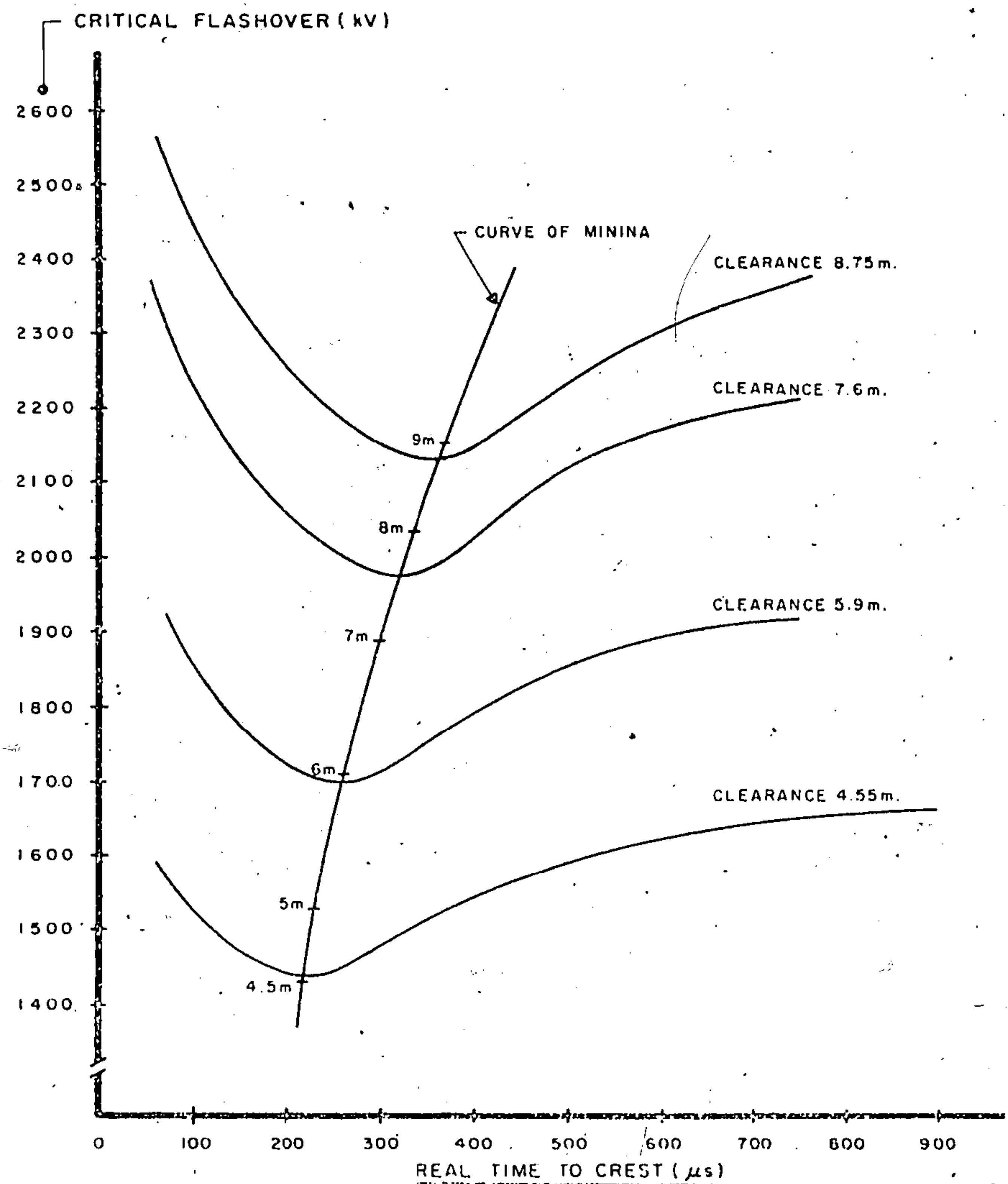


Fig. 6.4 — Positive Polarity 50% Breakdown Voltage of Tower Window Models.

Line Insulation Characteristics	Highest Voltage for Equipment		
	362	765	1200
Lightning			
BIL of Apparatus	1050	1800	2550
Clearance (500 kV/m) (m)	2	3.5	5
Switching			
Statistical Overvoltage (p.u.) (2%)	2.5	1.6	1.6
Statistical Overvoltage (U_2) (kV)	735	1000	1560
Statistical Safety factor	1.15	1.15	1.15
Statistical Withstand (U_{90}) (kV)	850	1150	1800
Tower C.F.O. (U_{50}) (kV) ($\sigma = 5\%$)	910	1240	1950
Clearance (600 d $^{0.6}$) (m)	2	3.5	7
Power Frequency			
Insulator Length (150 kV/M RMS L-L) (M) (Based on medium pollution and standard insulators).	2.5	5	8
Number of Conductors per Phase	2	4	8

Table 6 — Effect of Voltage Stresses.

at 1200 kV the number of conductors per phase will determine the tower cost. As shown on Table 6, at 765 kV and above the clearance is based on the switching surge.

Thus the emphasis is on reducing the switching overvoltages. Among the three groups mentioned previously, the only one which does not affect the tower dimension is the power-frequency overvoltage.

CHAPTER 7

HIGH VOLTAGE PHENOMENA

The increased use of extra-high-voltage transmission lines and the common aspects of corona (radio, television influence and corona loss), have become very important in the design of transmission lines. Over the years, studies have ~~been~~ made about corona and its affects upon the operation of a power system. Corona is the cause of power loss as well as radio and television interference. It is due to ionization of the air and occurs when the potential of a conductor in air is raised to such a value that the dielectric strength of the surrounding air is exceeded. The discharge around the line conductors is accompanied by a sound and odor of ozone.

Investigating the causes of radio and television interference and devising methods to minimize their effects, is an area of great concern [24]. These are two distinct sources of noise, that is, gap noise and corona noise. Both sources can cause radio and television interference.

Gap generated noise is more common and is created when arcing exists between two spaced electrodes. In order to correct this tightening the connections or bonding the hardware is required. Fig. 7 shows that gap noise does not decrease with increasing frequency [24]. There

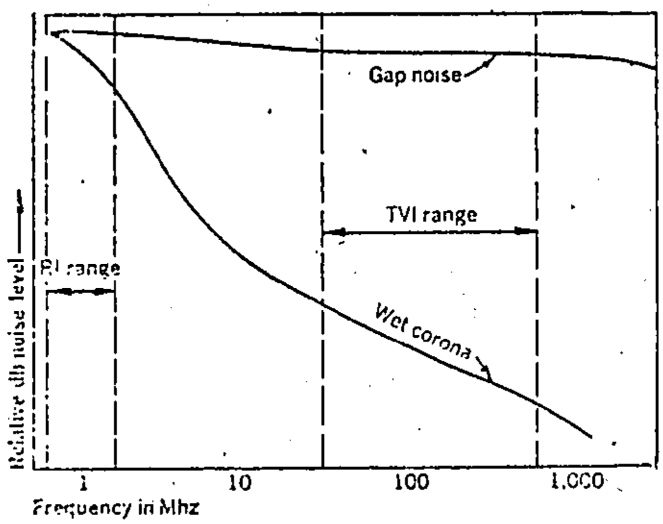


Fig. 7 — Gap Noise vs Frequency.

is about as much noise in the radio broadcast range as there is in the TV range. Also it shows that corona noise is greatly decreased with increasing frequency, which explains why it is sometimes difficult to measure corona noise at television frequencies.

7.1 Corona Loss

Clade and Gary have determined the effect of conductor and cage dimensions through theoretical and experimental work and have introduced a quantity that depends only on the surface conditions and on the surface gradients [25]. This quantity is called reduced loss and permits the corona loss computation of any conductor configuration, once its geometry is known. The relation between reduced loss P_N and measured loss P is given by [25]

$$P = KP_N \quad \ldots\ldots\ldots\ldots \quad 7.1$$

where

$$K = \frac{f}{50} \frac{(nrc)^2 \log_{10}(R/r_e) \log_{10} 25\sqrt{nr}/r_e}{\log_{10} R/25\sqrt{nr}} \ \mathrm{cm}^2$$

and

$c = 1 + 0.3/\sqrt{r}$ (PEEK's COEFFICIENT)

n = number of subconductors

r = radius of subconductors cm

R = radius of equivalent potential zero cylinder

r_e = equivalent radius of bundle conductor cm

f = frequency

7.2 Radio Interference

One of the important variables affecting radio-interference generation and the radio-interference level of transmission lines is the electric field at the surface of the conductor, a field directly proportional to voltage.

The radio-interference generation is described by [26].

$$SD[GD] = K_G \, 10^{\frac{G - G_0}{C}}, \quad \frac{A^2 s}{cm^2} \quad \ldots\ldots\ldots\ldots \; 7.2$$

where

SD[GD] = spectral density of generation density

G = conductor surface gradient

G_0 = corona-starting gradient

C, K_G = empirical constants.

Also, G_0 is given by:

$$G_0 = (SF)30\,000 \left(1 + \frac{.0301}{\sqrt{r}}\right) \text{ V/cm} \quad \ldots\ldots\ldots \; 7.3$$

where: SF = surface factor.

The RI generation equation can be written as follows:

$$SD[GD] = 10 \frac{(G - G_0)}{C} + 10 \log K_G \quad \text{(db)} \quad \ldots\ldots \; 7.4$$

The RI generation per unit length of conductor is given by:

$$SD\,[GD] = r \int_0^{2\Pi} \left(1 + \psi \frac{2r}{s} \cos\theta\right)^2 SD[GD]\, d\theta \quad \frac{A^2 \cdot s}{m} \quad \ldots \; 7.5$$

where $\psi = (m - 1) \sin\left(\frac{\Pi}{m}\right)$

s = bundle spacing

7.3 AUDIBLE NOISE

Audible noise is a quantity which is dependent on the electric field near the conductor surface and on the surface and atmospheric conditions. Assuming a uniform distribution of noise sources on the conductor, the relation between the acoustic power J, reaching a measuring point near a line and acoustic power density A is given by [25].

$$J = \int_{\text{line}} \frac{A\,dx}{4\Pi(R^2 + x^2)} + K \int_{\text{line}} \frac{A\,dx}{4\Pi(Z^2 + x^2)} \quad \ldots\ldots 7.6$$

where

A = power generated per unit conductor length

R = distance measuring point to line

Z = distance measuring point to "image" of line

X = variable distance along conductor

K = reflection coefficient

CHAPTER 8

ELECTRICAL AND MECHANICAL ASPECTS OF BUNDLE CONDUCTORS

For the past one quarter of a century the use of bundled conductors with 2, 3, or 4 subconductors has become solidly established for the extra-high-voltage transmission lines.

A "bundle conductor" is a conductor made up of two or more "sub-conductors" and is used as one phase conductor. Bundle conductors are also called duplex, triplex, and so on, referring to the number of sub-conductors and are sometimes referred to as a grouped or multiple conductors.

The increase in transmitting capacity justifies economically the use of bundle conductors in extra-high-voltage transmission systems. Bundle conductors reduce line reactance, consequently increasing the surge-impedance-loading of the line. Mostly, the bundle conductor size affects tower loading, real losses, corona loss and radio influence levels.

Experience has shown that the use of extra-high-voltage transmission, creates electrical constraints bringing up unacceptable mechanical burdens on the structures which in turn forces power system designers to establish a much closer coordination between the electrical and mechanical aspects of extra-high-voltage lines.

8.1 ELECTRICAL DESIGN CRITERIA

Thermal capacity and losses are the main factors which have to be considered in the choice of conductors. In high-voltage lines these do not conflict with the mechanical design of structures. In the case of extra-high-voltage lines, corona is the most important factor and voltage gradients must be limited in order to keep radio and audible noise within acceptable limits. This can be done by increasing the cross-section of the conductors and also by bundling the conductors and therefore thermal capacity is not reached. However, bundle conductors create mechanical problems caused by oscillations and icing. Therefore, attention must be given to the size and number of conductors used, so that the electrical performance is within acceptable limits.

8.2 ELECTRICAL DESIGN CONSIDERATIONS OF BUNDLED CONDUCTORS

The electrical design of bundled conductors is a wide and complicated subject and is out of the scope of this presentation. But, because of the interaction of electrical and mechanical criteria, it is important to outline a few points relevant to the mechanical behaviour of the bundle. The factors leading to the choice of a bundle configuration are electrical in nature. These are related to electrostatic field and gradient distribution of a system of parallel subconductors. For a given line capacity the electrical engineer can use the phase voltage, the number and size of subconductors, the dimension of the bundle and its geometry to optimize the design. Hydro-Quebec has chosen a 4-bundle conductor with 457 mm spacing for its 735 kV network. The determination of the radius of the single conductor equivalent to the bundle with respect to maximum surface gradient is used to indicate good values of the rate of the spacing to conductor diameter for a given number of subconductors. For values of $n = 4, 6, 8, 10, 12$; $A/d = 12.5, 11.3, 10, 9.5, 9$

where: n = number of subconductors

A = subconductor spacing

d = subconductor diameter

Fig. 8.2 shows a plot of R_e/R versus A/R for $n = 6$. The heavy lines indicate the practical limts for B/R, where:

B = distances between two phases

R_e = radius of single conductor equivalent to the bundle for maximum gradient

R = radius of subconductor

The best choice of A/R corresponds to the highest value of R_e/R and seems to be 22.5 for bundle of 6 conductors.

8.3 MECHANICAL PERFORMANCE OF BUNDLED CONDUCTORS

In the extra-high voltage range a single horizontal circuit is used. Spans of 300 m to 400 m are used resulting in tower heights of 40 m for good designs. Normal single-conductor practice is followed for the evaluation of tower loading due to wind, ice or conductor breakage [27], [28]. The transverse wind load is considered as being that on the total number of subconductors. The longitudinal loading for broken conductor conditions assumes either one broken conductor or unequal ice loading. The ice loading is also assumed to be equal on each subconductor [28].

Cloud icing is the most important ice formation on conductors. It happens when a low cloud layer containing supercooled droplets is moving through a transmission line. It has been observed that the rate

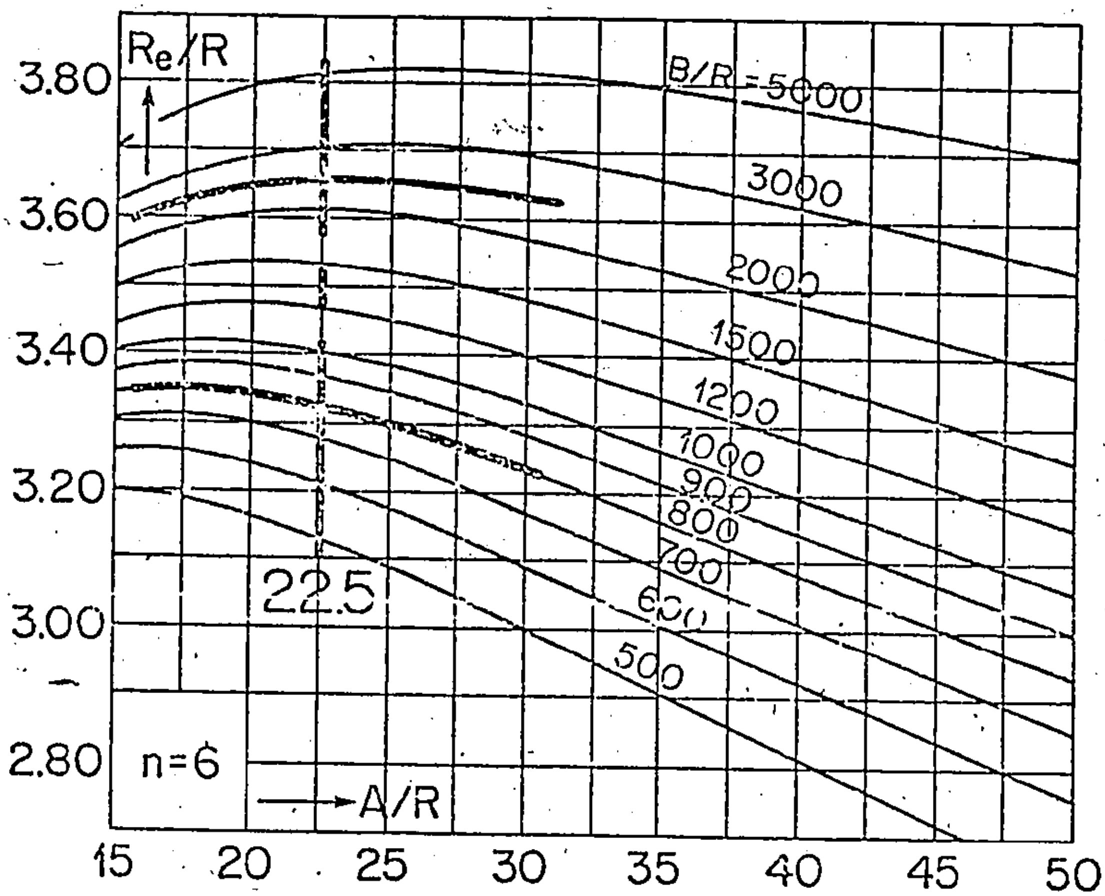


Fig. 8.2 — Plot of Re/R vs A/R.

of ice formation on large diameters is smaller than for a small diameter object [29]. For areas with heavy icing conditions the smaller the number of subconductors the less the icing load will be.

It is difficult to evaluate precisely the actual ice loading likely to occur on a line because of the lack of information on the meteorological conditions where the lines are built.

The spacer strength is dependent on non-cyclic forces due to short circuit loads and differential ice loading. The spacer forces due to short circuit currents with bundles of n subconductors have been evaluated by Manuzio [30]. The maximum spacer load is proportional to the ratio n-1/n, resulting in a decreased load with an increase in the number of conductors for similar conductor tension and short circuit current.

Usually unequal ice loading represents the worst spacer load conditions. Fig. 8.3 shows typical types of spacers.

The dynamic performance of bundled conductors is governed by three vibration phenomena:

a) conductor galloping (.1 - 1 Hz)

b) aeolian vibration (10 - 100 Hz)

c) subspan oscillation (1 - 3 Hz)

Galloping occurs with winds from 5m/s-15m/s and is associated with ice formation on conductors.

Aeolian vibration is associated with low wind velocity below 10 m/s and can cause fatigue damage to the conductors and clamp loosening.

Bundled conductors are protected against aeolian vibrations by

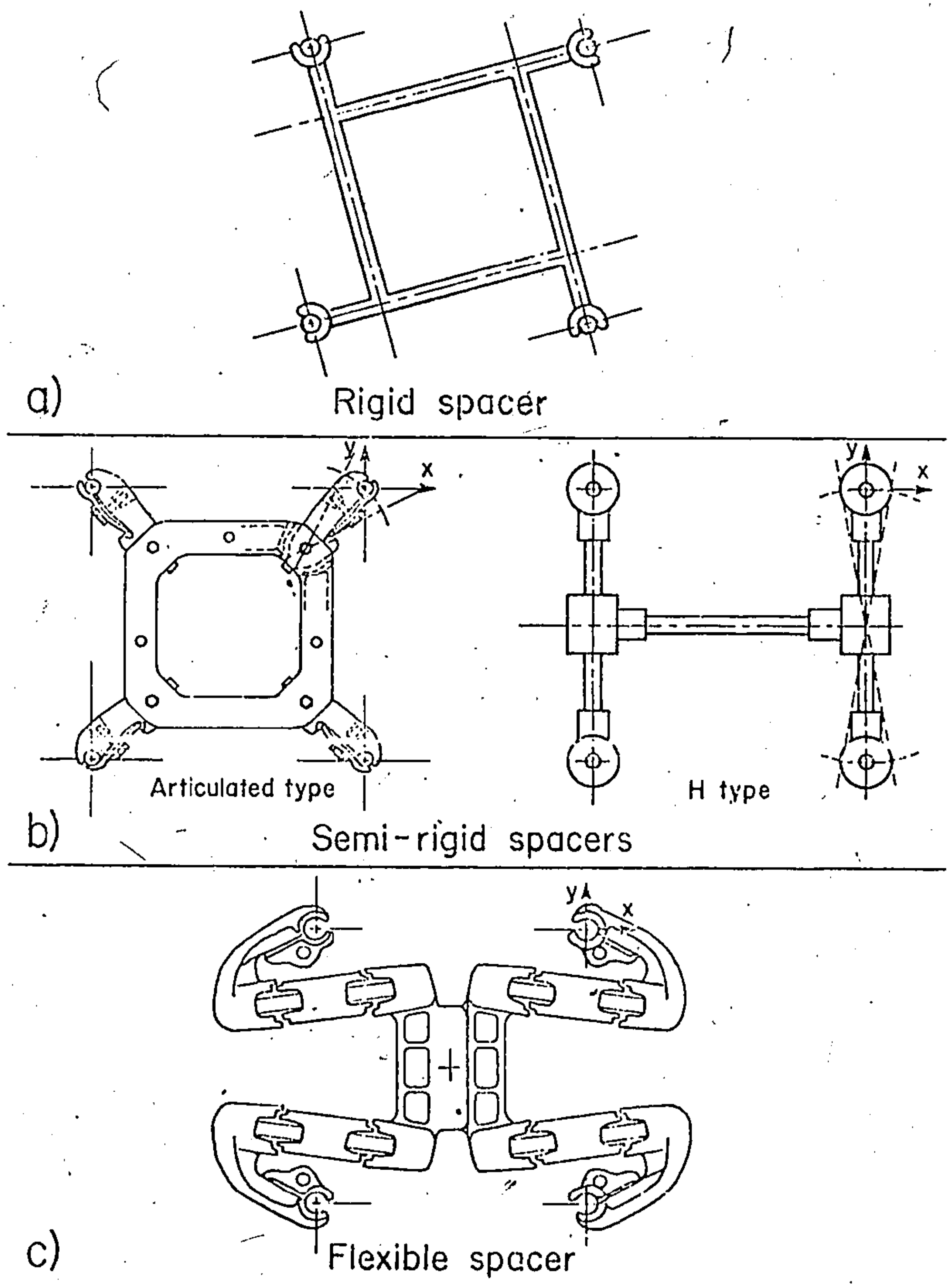


Fig. 8.3 — Typical Types of Spacers.

the use of spacer-dampers or by the use of a combination of spacers and dampers. In general, the magnitude of aeolian vibration diminishes with the increase of number of subconductors.

CHAPTER 9

EXTRA-HIGH-VOLTAGE SUBSTATIONS

In recent years there has been considerable discussion on the standardization of substations for industrial and commercial distribution. For bulk transmission of power, substation standardization is more difficult, since the single-line diagram will vary considerably, depending on the importance and function of the substation. For the Hydro-Quebec James-Bay project a number of basic station design variates were required. Stations differ in the number of circuits and step down transformers. The choice of a single-line diagram for the extra-high-voltage substations depends on the planning criterion, which stipulates that the system must be stable if a permanent fault occurs on a line.

The objective of system engineers was to design substations such that failure of two lines at the same time would be impossible. Also, equipment maintenance should be done without interrupting the function of the system [31].

9.1 DESIGN EVALUATION FACTORS

The choice of the substation arrangement to be used is dependent upon the relative importance assigned to such items as safety, reliability, simplicity of relaying, flexibility of operation, first cost, ease of maintenance, available ground area, location of connecting lines, provisions for expansion and appearance.

A reasonable criterion for evaluating the basic designs is that each shall fulfill certain functional requirements, be economical in the space used, if space is a factor and comply in the most practical way with fundamental conditions for satisfactory construction, safety, operation, maintenance and expansion.

For safety and reliability it is essential that adequate clearances be provided to live parts. Main buses should preferably be on a single level, not one above the other. Electrical clearances should comply with the minimum recommendations plus a safety factor. Insulation coordination should be checked for uniform voltage levels. Lightning arresters should be installed where is required. Personnel should be protected as much as possible from any ground voltage gradient resulting from large ground-fault currents.

By flexibility is meant the ability to take circuit breakers, buses, etc. out of service for maintenance without interruption to service. Increased flexibility means increased cost and more complicated relaying and operation.

9.2 Basic Design Connections

Most substations will conform to one or the other of the following basic arrangements [32].

a) main and transfer bus
b) breaker-and-a-half with two main buses
c) double breaker, double bus
d) ring-bus

Most stations initially start with a ring bus scheme which includes both step-down and generating unit transformers with provision for expansion to a 1 1/2 breaker scheme in the future.

Substations used on the 735 kV transmission project for Hydro-Quebec, have two levels of busbars in order to obtain lower structures. Further, it uses two kinds of substations [31].

a) Transformer substations located at the generation, and

b) The switching stations located along the lines as shown on Fig. 9.2.

Substations were selected in order to full-fill some conditions as follows:

a) Maintenance of equipment to be readily done without interrupting service.

b) If there exists a fault on equipment which is connected directly to the line no more than one line loss is permitted.

c) To use only two levels of busbars in order to reduce the height of structures and maintenance to be easier.

9.3 Selecting a Single Line Diagram

According to the criteria for substations mentioned earlier, the designer must choose and design a single line-diagram accordingly. Fig. 9.3 (a) shows a ring-bus arrangement having the advantage of requiring only one breaker for each circuit and only one breaker can be taken out of service for overhaul without de-energizing any of the lines. A failure of a bus insulator will interrupt service to a single line only. Usually bus insulator and line insulators are cleaned at the same time. In the case of a second line fault while one of the circuit breakers is out of

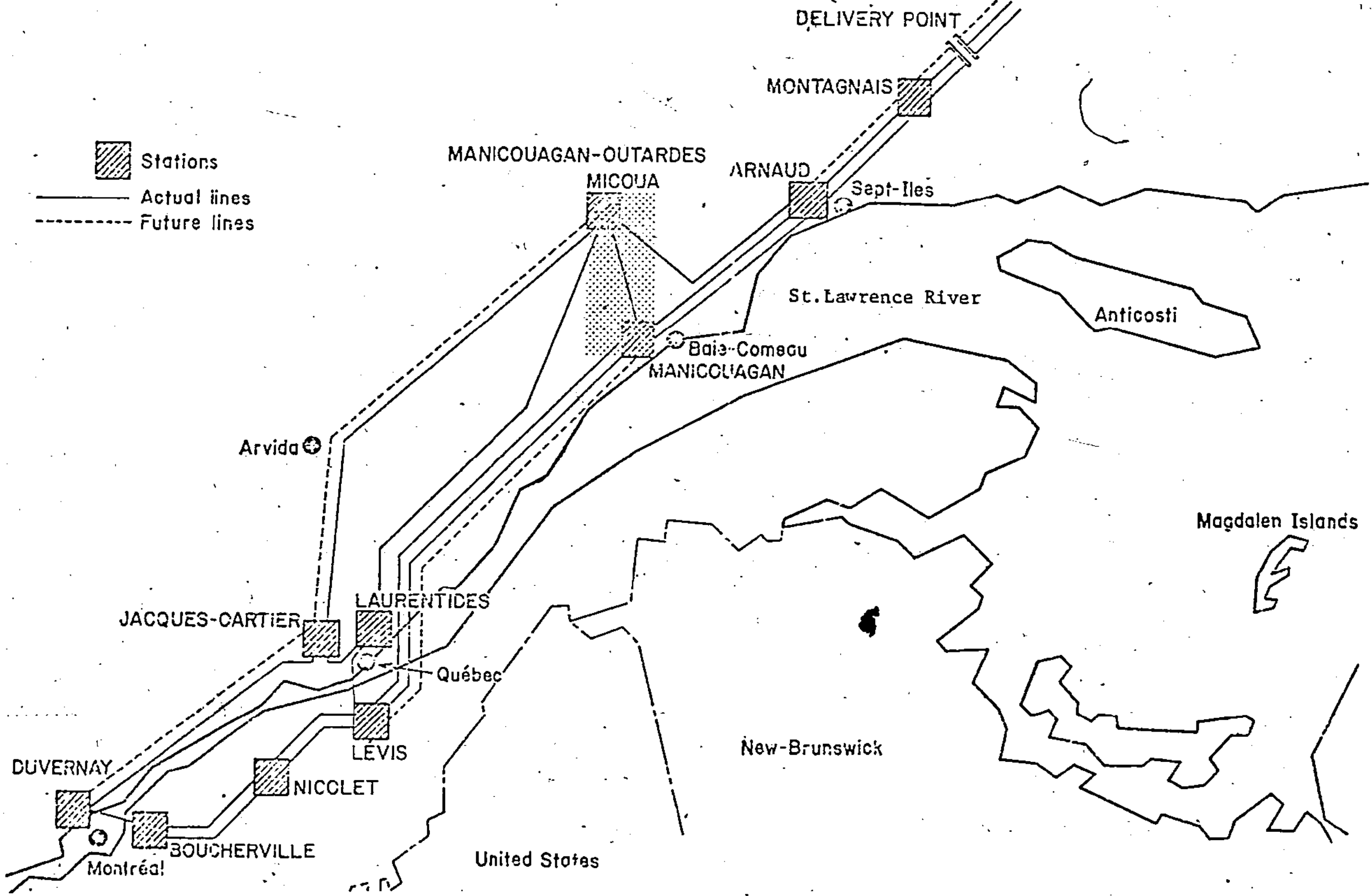


Fig. 9.2 — Hydro-Québec 735 kV Network.

service for overhaul, the ring bus would be open at two points which might separate the source of power from the load.

The other possible scheme which can be used is the breaker and a half. This arrangement provides flexibility and reliability and uses fewer circuit breakers. Normal operation would have both busses energized and all circuit breakers closed. However, either bus or any circuit breaker can be removed from service without interruption of power flow. Fig. 9.3 (b) shows a breaker-and-a half configuration with two main busses.

Also the main and transfer bus arrangement provides a means of isolating any individual circuit breaker for overhaul or maintenance work without interrupting service to the lines. One possible arrangement is shown in Fig. 9.3 (c) [33].

9.4 General Description of Substation

One of the many substations of the James-Bay project is the LG-Z substation. This will be built in a mountainous region and will be located above the generating station. Sixteen shielded busbar shafts, each about 450 feet high, will link the generators to the transformers. The rated current in the buses will be 17 200 A at 13.8 kV [31]. The substation will have a capacity of nearly 6 million kVA and will feed four 735-kV transmission lines. The substation will measure 580 by 366 meters.

The voltage levels in the substation will be 15 and 735 kV, which is something of an innovation as underground generating stations built to date have had three voltage levels, namely 15, 315, and 735 kV. Studies have shown that it is more economical to eliminate the intermediate

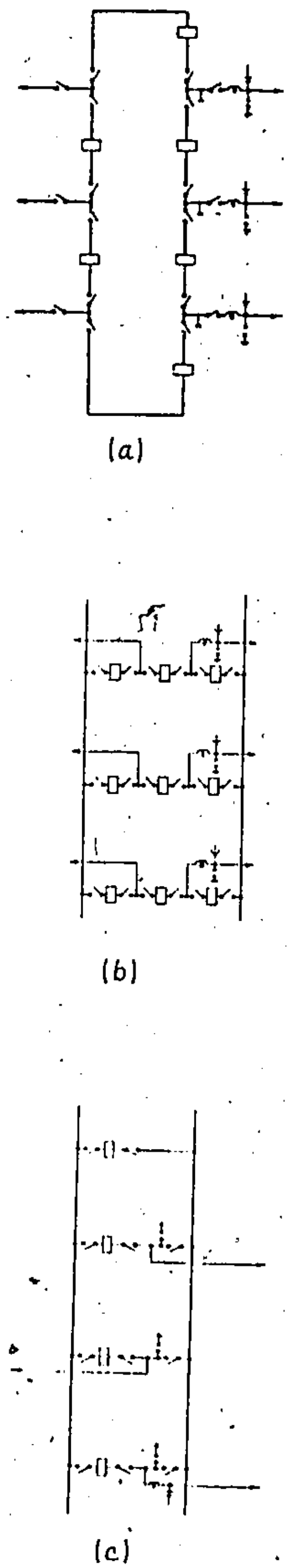


Fig. 9.3 — *Single-Line Diagrams.*

transformers (315 kV) located indoors. Fig. 9.4 shows the LG-2 substation [31].

9.5 CHARACTERISTICS OF THE ELECTRICAL EQUIPMENT

Fig. 9.4 shows the single-line diagram of the LG-2 substation. Fig. 9.5 shows where it is located.

The following characteristics apply to all the equipment:

Ambient temperature:	from $-50^{o}C$ to $+ 40^{o}C$
Frequency:	60 Hz
Rated voltage:	735 kV
Max. voltage:	765 kV
B.I.L.:	2100 kV
Radio interference:	500 µV

Each power transformer will consist of a bank of three single-phase step-up units with two low-voltage windings. It will have the following characteristics:

Rated capacity:	700 MVA
Temperature rise:	$65^{o}C$
Cooling:	OFAF
Ratio:	735/13.8 - 13.8 kV
Connection:	YΔΔ
Nominal impedance with LV winding in parallel:	15%

The shunt reacotrs shall have the characteristics as follows:

Rated capacity of three-single phase units:	165 Mvar
Temperature rise:	$65^{o}C$
Connection:	grounded Y

The air blast circuit breakers will have the following characteristics:

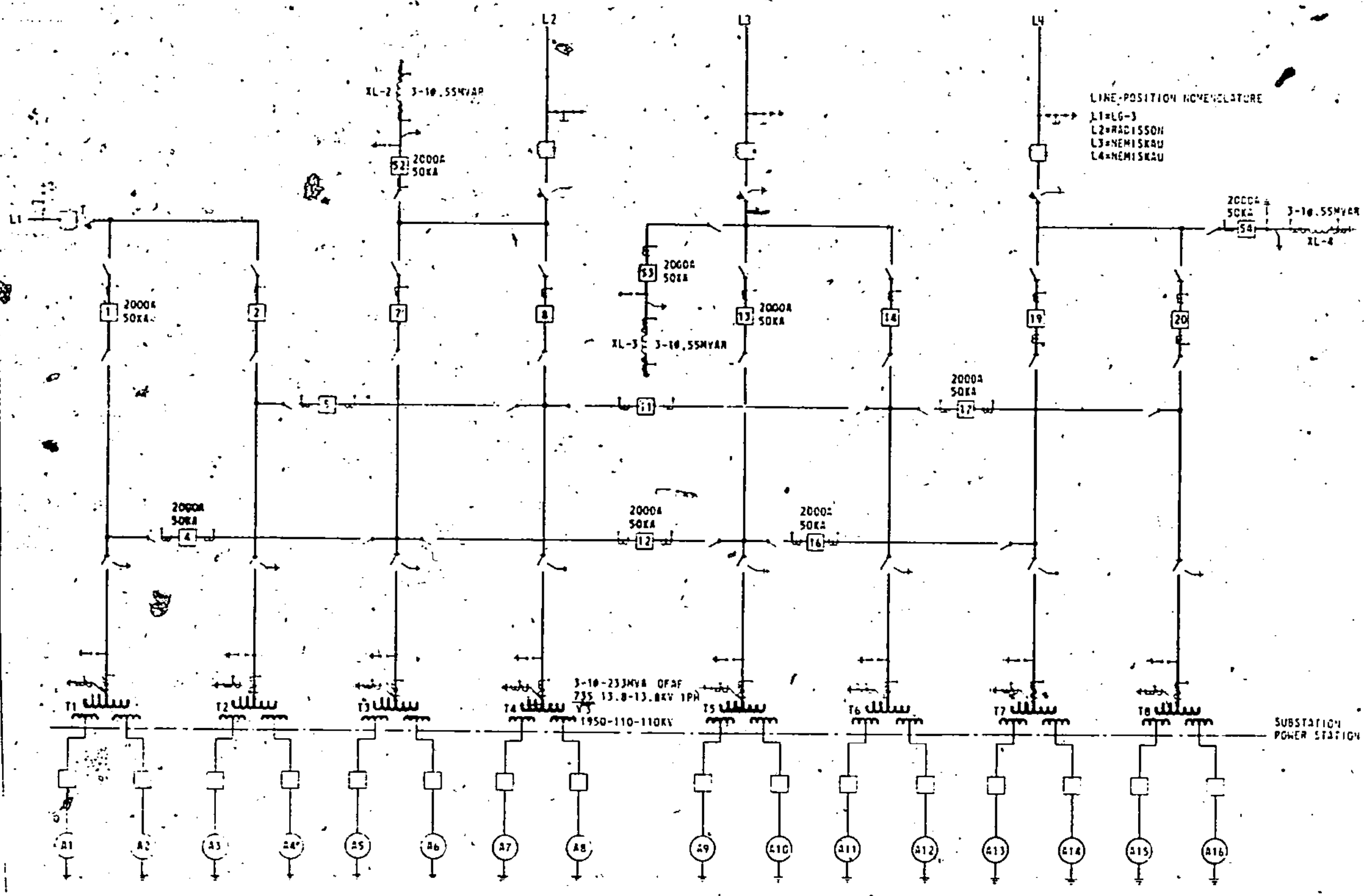


Fig. 9.4 — Single-Line Diagram for LG 2 Substation.

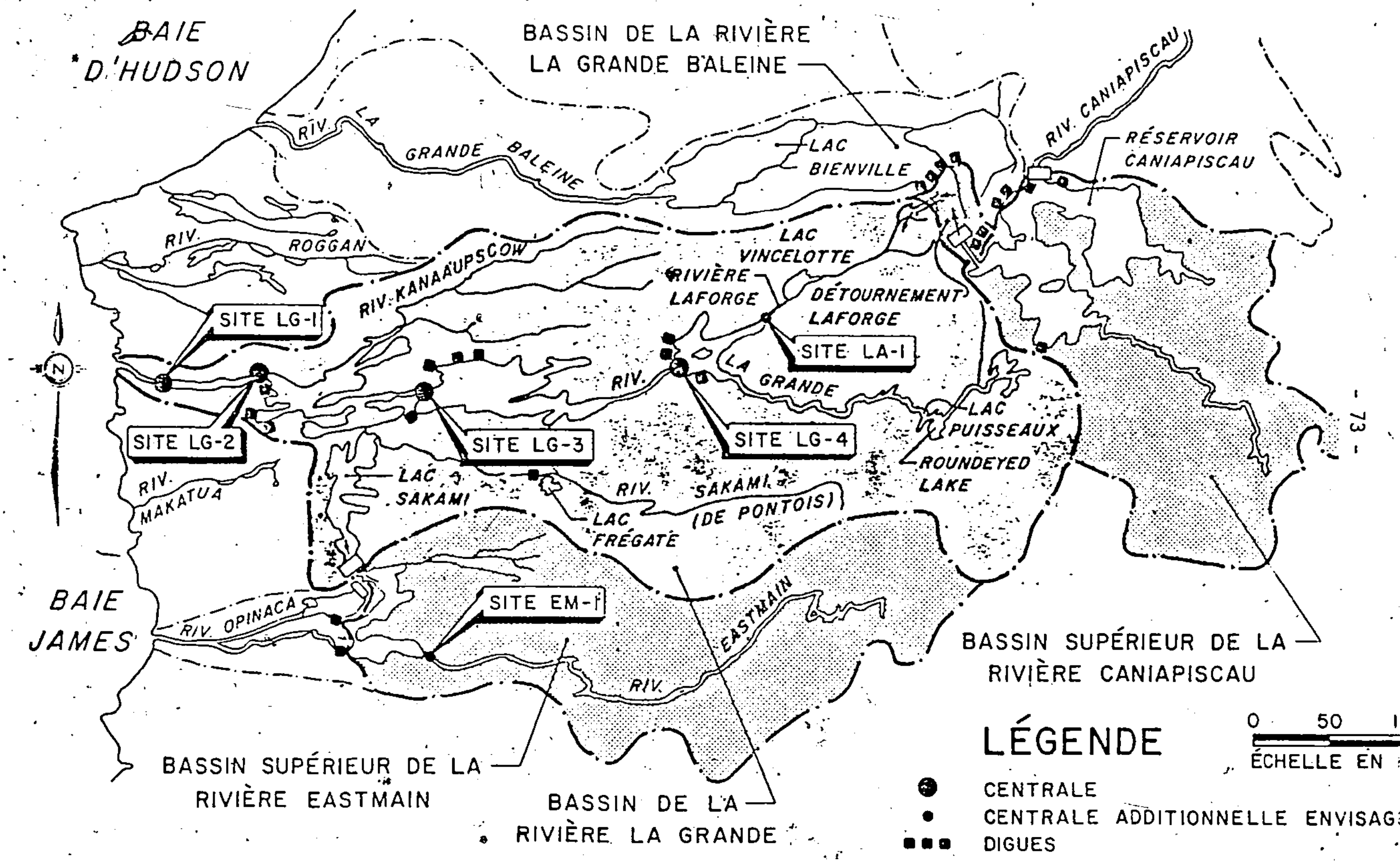


Fig. 9.5 — Complexe La Grande.

Continuous current rating: 4000 A and 2000 A
Rated short-circuit capacity: 50 KA
Maximum total duration of break: .05 s

Lightning arresters will have a voltage rating of 612 kV and B.I.L. of 1400 kV.

9.6 Characteristics of Power Transformers

The power transformer for the LG-Z substation will be a prototype. For the first time, a transformer will have a ratio of 735/13.8 - 13.8 kV. The low voltage side will have two windings, each connected to a 370 MVA generator [31]. Also there will be protection against flames from a faulty transformer. A fire-wall between transformers will confine flames and an oil-retention pit will be provided to avoid environmental pollution as shown in Fig. 9.6.

9.7 Switching Equipment

The most commonly used extra-high-voltage circuit breakers are the compressed-air type. Oil-circuit breakers have been available for a long time but they have not gained great acceptance by utilities. The SF6 circuit breaker is a recent product and will be more extensively applied to compact substations. Also, disconnect switches are used for extra-high voltage transmission. Among the above switching equipment, the oil-circuit breaker has relatively less trouble and shorter down-time.

9.8 Control Equipment

Fig. 9.8 shows a typical protection block diagram. Current transformers used in protection circuits will have a ratio of 4000/2000

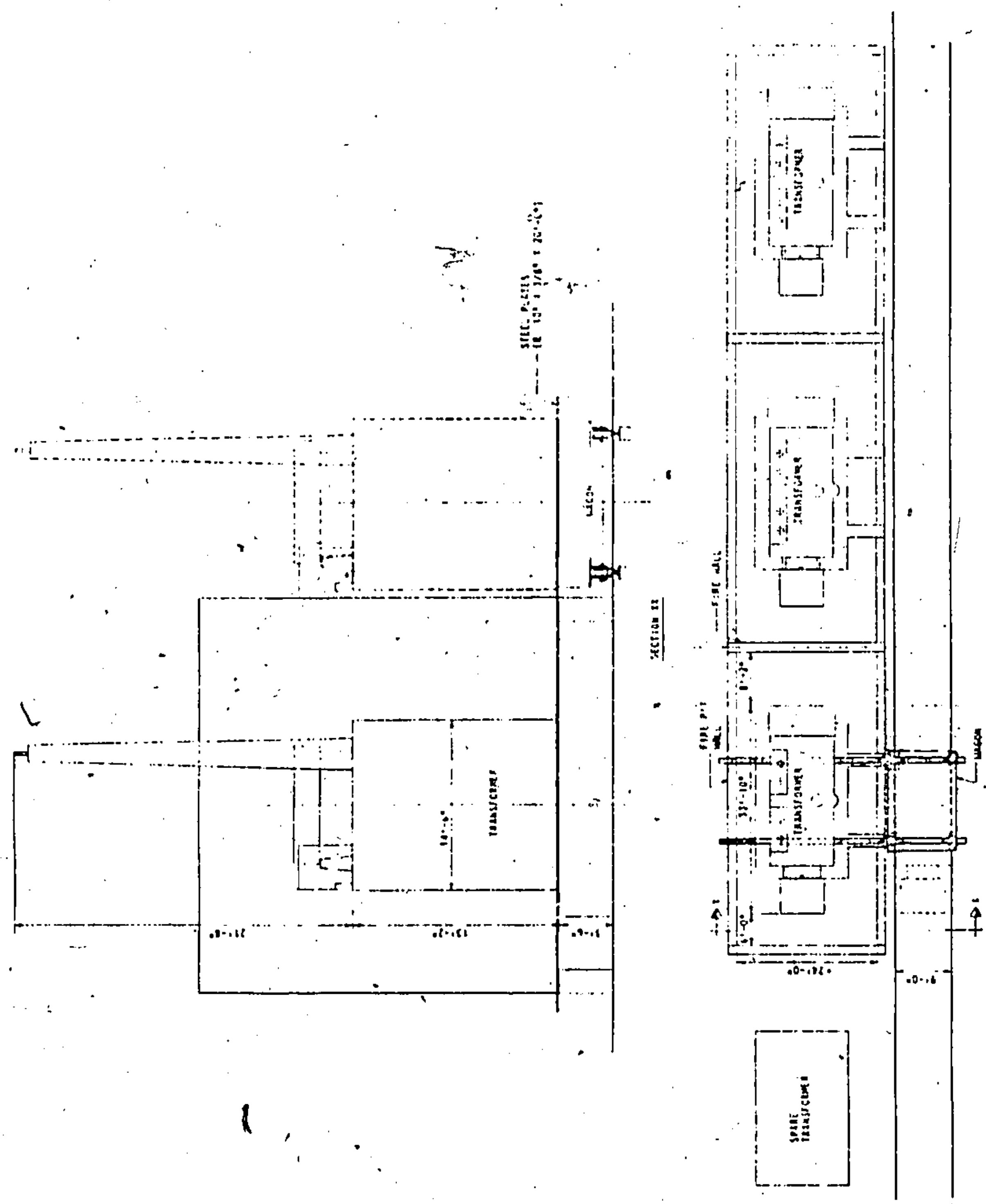


Fig. 9.6 — Plan View.

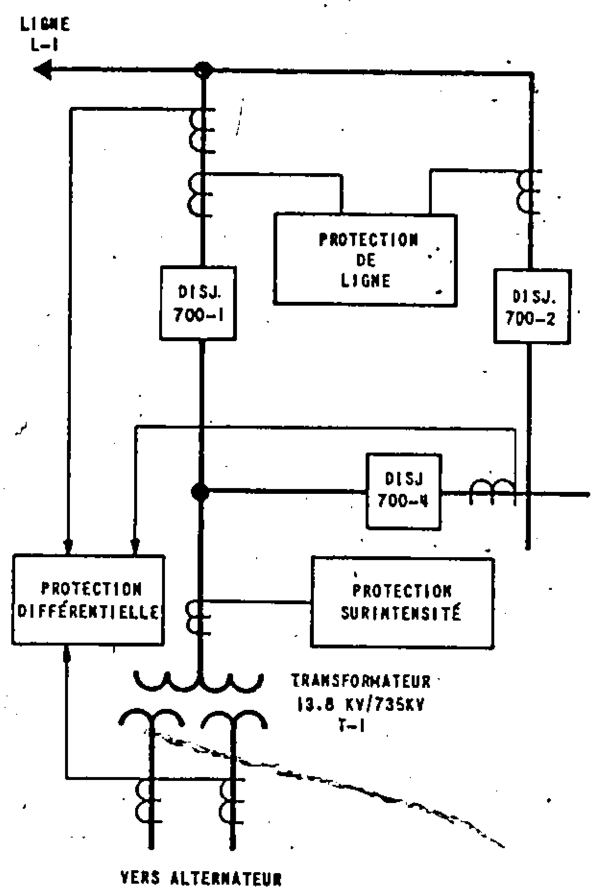


Fig. 9.8 — Typical Protection Block Diagram.

to 1A and they must withstand a maximum symmetrical short-circuit current of 50 kA. The control wiring is fed from 24 volts dc batteries, with number 9 AWG wiring.

The breaker 700-1 will be tripped simultaneously by L-1 line protection and by the differential protection of transformer T-1. The line protections tripping order should reach breakers 700-1 and 700-2. The transformer protections tripping order should reach breakers 700-1, 700-4, and the two 13 kV breakers on the busbars coming from the generators [31].

CHAPTER 10

CONCLUSIONS

There are various ways to support the voltage of a system, following the loss of a line. At the sending end, static excitation systems can hold the terminal bus voltage. Also, at an intermediate bus, capacitor banks are needed to maintain a good voltage at peak load, linear reactors are needed to absorb reactive power during light-loads, saturable reactors are installed to prevent excessive temporary overvoltages due to load rejection and synchronous compensators are provided to help maintain the voltage under disturbed conditions. All the above-mentioned equipment effectively break the transmission line into shorter lengths and, with each section supported by a fast-acting reactive power controlling device, the overall stability of the system is improved.

Another way of achieving stability of the system is to use series capacitors. Series capacitance may be required for the condition of highest circuit reactance, but may not be needed for the normal condition with all lines in service. The series capacitors must be used in two ways described in the project, where the choice between these two arrangements depends upon the relative advantages from the stability point of view.

For the design of 735 kV extra-high-voltage system, analytical studies were made with the help of a digital computer, in order to get in consideration the best circuit. Importance and careful consideration was given to the system performance, priority to the stability of the system under different faults. The computer program tested the 735 kV system for stability under a three-phase fault at the bus near the generation station and a line-to-line fault at a sectionalized transmission line, with certain number of circuits and line compensation. The results showed that the system with 8 circuits and 60% compensation is stable under the imposed faults. In other cases was unstable for both fault conditions except for the case with two circuits and 90% compensation where the system is stable under the three-phase fault and unstable for line-to-line fault.

With the eventual use of bundle conductors for extra-high voltage transmission lines, the interaction of electrical and mechanical criteria become increasingly important. A great amount of work has been done for bundles of up to 4 conductors and that some of the answered researched could be already available.

In this major report no effort has been made to develop a standard high-voltage substation but it will be noted that some equipment are repeated in a number of layouts. The choice of arrangement will be dependend on the relative importance assigned to the design factors previously enumerated. This will depend on the judgment, prejudice and experience of those making the choice. As might be expected, no single basic design stands out as being superior to the others in all respects. All factors should be carefully reviewed and the design selected should be that which meets the requirements which are considered to be most important.

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APPENDIX

SAMPLE CALCULATIONS

a) The following procedure tests the 735 kV system, 600 miles in length, with 8 circuits and 60% compensation.

The per unit system is used for computation

$$Z_b = (kV)\ b/MVA)_b, \qquad Zpu = Z/Zb$$

here: $(kV)_b = 735$ kV

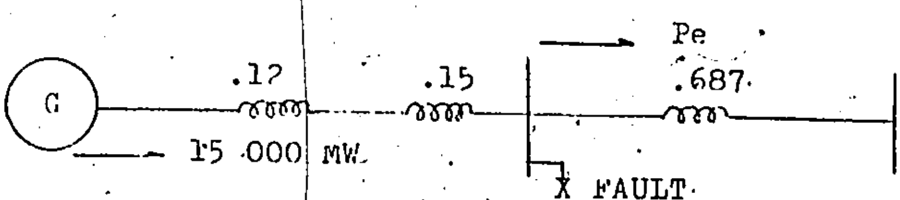
$(MVA)_b = 15\ 000$ MW

$$\therefore\ Z_b = 735^2/15\ 000 = 36\ \Omega$$

$$Z = .5 \times 600 \times \frac{.40}{8} = 15\ \Omega$$

$$X = .12 + .15 + \frac{Z}{Z_b} = .12 + .15 + \frac{15}{36} = .687$$

The equivalent circuit of the transmission line is as follows:



b) 3-phase fault on the bus near the generation station with 8 circuits, 60% compensation

$$X_T = .687$$

$$P_e = \frac{1 \times 1}{X_T} \sin\delta = 1 \longrightarrow \frac{1}{.687} \sin\delta = 1 \longrightarrow \delta = 43.5^0$$

$$P_e(\text{before fault}) = \frac{1}{.687} \sin\delta = 1.455 \sin\delta = 1 \longrightarrow \delta = 43.5^0$$

P_e (during fault) = 0

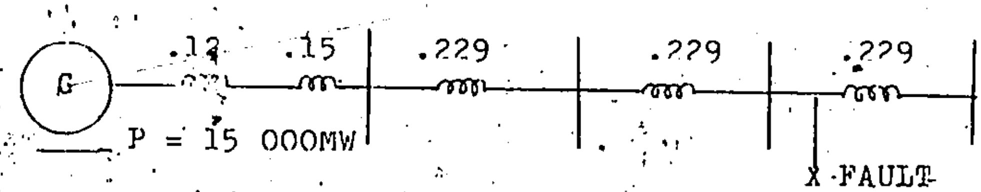
P_e (after clearing the fault) = 1.455 sin δ_n

The table below shows the computation under this condition.

clearing time (.05)

	0	.05	.10	.15	.20	.25	.30	.35	.40	.45
9 $P_{a(n-1)}$	0	4.5	9	3.245	-3.69	-3.96	5.256	-3.438		
$\Delta\delta_n$	0	4.5	13.5	16.74	13.05	9.09	105.64	-1.75		
δ_n	43.5	48	61.5	78.24	91.3	100.3	107.3	105.5		
P_e	1) 0) .5	0	0, 1.279 } .639	1.41	1.44	1.426	1.382	Stable		
P_a	.5	1	.36	-.41	-.44	-.426	-.382			

c) Line-to-Line fault on a sectionalized transmission line, with 8 circuits, 60% compensation. Transmission line will be as follows:



The per-unit reactance of the system is

$$X_T = .12 + .15 + \frac{Z}{Z_b}$$

where:

$$Z = .5 \times 400 \times \frac{F}{C} + .5 \times 200 \times \frac{F}{C-1}$$

$$= .5 \times 400 \times \frac{.40}{8} + .5 \times 200 \times \frac{.40}{7}$$

$$\therefore Z = 15.7$$

$$\therefore X_T = .12 + .15 + \frac{15.7}{36} = .706$$

$$\therefore P_e = \frac{1 \times 1}{X_T} \sin\delta = 1 \longrightarrow \frac{1}{.687} \sin\delta = 1 \longrightarrow \delta = 43.5^0$$

$$P_e(\text{before fault}) = \frac{1}{.687} \sin\delta = 1.455 \sin\delta = 1 \longrightarrow \delta = 43.5^0$$

$$P_e(\text{during fault}) = 0$$

$$P_e(\text{after clearing fault}) = 1.416 \sin\delta_n$$

The table below shows the computation under this condition.

	0	.05	.10	.15	.20	.25	.30	.35	.40	.45
$9Pa_{(n-1)}$	0	4.5	9	3.275	3.645	-3.9	-3.78	-3.87	-3.338	
$\Delta\delta_n$	0	4.5	13.5	16.77	13.125	9.225	5.445	1.575	-1.809	
δ_n	43.5	48	61.5	78.27	91.39	100.6	106.04	107	105.19	
P_e	$\left.\begin{matrix}1\\0\end{matrix}\right\}.5$	0	$\left.\begin{matrix}0\\1.272\end{matrix}\right\}.636$	1.405	1.434	1.42	1.43	1.376		Stable
P_a	1	1	.363	-.405	-.434	-.42	-.43	-.376		

More details for other test with different amount of compensation and circuits are shown on the computer print out.

```
      PROGRAM TEST(INPUT,OUTPUT)
1     READ*,A,B,C,F
      IF(A.EQ.0.0)STOP
      PRINT 208
208   FORMAT(1H1)
110   X=ZB=DDN=DN=PE=PA=Y=Z1=W=XX=YY=0.0
      PRINT 200
200   FORMAT(15X,*POWER(MW)*,10X,*VOLTAGE(KV)*,10X,*NO.OF LINES*,10X,
     +*AMOUNT OF COMPENSATION*)
      PRINT 201,A,B,C,F
201   FORMAT(15X,F9.2,10X,F7.2,16X,F3.1,26X,F5.2)
      ZB=B**2/A
      READ*,H
      IF(H.EQ.1.0)GO TO 2
      PRINT 202
202   FORMAT(10X,*3 PHASE FAULT ON THE BUS NEAR THE STATION*)
      Z=0.5*600.0*F/C
      X=0.12+0.15+Z/ZB
      LIM=0
      GO TO 3
2     PRINT 205
205   FORMAT(10X,*LINE TO LINE FAULT*)
      Z=0.5*400.0*F/C+0.5*200.0*F/(C-1.0)
      X=0.12+0.15+Z/ZB
      LIM=1
3     DN=DN+ASIN(X)
      PE=PE+0.5
      PA=PA+1.0-PE
      RA=180.0/3.14159
      Y=DN*RA
      PRINT 203
203   FORMAT(10X,*DDN*,15X,*DN*,15X,*PE*,15X,*PA*)
      PRINT 204,DDN,Y,PE,PA
204   FORMAT(6X,F9.3,8X,F9.3,7X,F9.3,7X,F9.3)
      DDN=DDN+9.0*PA/RA
      DN=DN+DDN
      PE=0.0
      PA=1.0-PE
      Y1=DDN*RA
      Y2=DN*RA
      PRINT 204,Y1,Y2,PE,PA
      DDN=DDN+9.0*PA/RA
      DN=DN+DDN
      PE=(1.0/X)*SIN(DN)/2.0
      PA=1.0-PE
      Z1=DDN*RA+Z1
      W=DN*RA+W
      PRINT 204,Z1,W,PE,PA
10    DO 11 J=1,10
      AA=J/J
      DDN=DDN+(9.0*PA/RA)*AA
      DN=DN+DDN
      PE=(1.0/X)*SIN(DN)
      PA=1.0-PE
      XX=DDN*RA+XX
      YY=YY+DN*RA
      PRINT 204,XX,YY,PE,PA
```

```
      P=DN-DDN
      IF(DN.LT.P)GO TO 20
   11 XX=YY=0.0
      PRINT 206
  206 FORMAT(30X,*UNSTABLE*/)
      IF(LIM.EQ.1)GO TO 1
      GO TO 110
   20 PRINT 207
  207 FORMAT(30X,*STABLE*/)
      IF(LIM.EQ.1)GO TO 1
      GO TO 110
      END
```

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	8.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	43.353	.500	.500
4.500	47.853	0.000	1.000
13.500	61.353	.639	.361
16.747	78.101	1.425	-.425
12.919	91.019	1.456	-.456
8.811	99.830	1.435	-.435
4.893	104.724	1.409	-.409
1.214	105.937	1.401	-.401
-2.393	103.545	1.416	-.416

STABLE

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	8.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	44.937	.500	.500
4.500	49.437	0.000	1.000
13.500	62.937	.630	.370
16.827	79.763	1.393	-.393
13.287	93.051	1.414	-.414
9.564	102.614	1.382	-.382
6.129	108.743	1.341	-.341
3.063	111.806	1.314	-.314
.233	112.039	1.312	-.312
-2.578	109.460	1.335	-.335

STABLE

60% Line Compensation

POWER(MW) 15000.00 | VOLTAGE(KV) 735.00 | NO.OF LINES 5.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	50.335	.500	.500
4.500	54.835	0.000	1.000
13.500	68.335	.604	.396
17.067	85.402	1.295	-.295
14.413	99.816	1.280	-.280
11.893	111.709	1.207	-.207
10.031	121.740	1.105	-.105
9.088	130.827	.983	.017
9.241	140.068	.834	.166
10.737	150.805	.634	.366
14.034	164.839	.340	.660
19.976	184.814	-.109	1.109
29.957	214.771	-.741	1.741

UNSTABLE

POWER(MW) 15000.00 | VOLTAGE(KV) 735.00 | NO.OF LINES 5.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	54.237	.500	.500
4.500	58.737	0.000	1.000
13.500	72.237	.587	.413
17.219	89.456	1.232	-.232
15.128	104.584	1.193	-.193
13.394	117.977	1.088	-.088
12.599	130.576	.936	.064
13.174	143.750	.729	.271
15.616	159.366	.434	.566
20.707	180.073	-.002	1.002
29.721	209.794	-.612	1.612
44.232	254.027	-1.185	2.185
63.895	317.922	-.826	1.826

UNSTABLE

70% Line Compensation.

POWER (MW)	VOLTAGE (KV)	NC.OF LINES
15000.00	735.00	4.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	52.243	.500	.500
4.500	56.743	0.000	1.000
13.500	70.243	.595	.405
17.143	87.386	1.264	-.264
14.772	102.158	1.236	-.236
12.643	114.801	1.148	-.148
11.310	126.111	1.022	-.022
11.113	137.225	.859	.141
12.382	149.607	.640	.360
15.623	165.230	.322	.678
21.721	186.952	-.153	1.153
32.099	219.050	-.797	1.797
48.271	267.321	-1.263	2.263

UNSTABLE

POWER (MW)	VOLTAGE (KV)	NC.OF LINES
15000.00	735.00	4.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	58.045	.500	.500
4.500	62.545	0.000	1.000
13.500	76.045	.572	.428
17.353	93.398	1.177	-.177
15.764	109.162	1.113	-.113
14.744	123.906	.978	.022
14.941	138.847	.776	.224
16.960	155.807	.483	.517
21.613	177.420	.053	.947
30.136	207.556	-.545	1.545
44.043	251.598	-1.118	2.118
63.108	314.706	-.838	1.838
79.647	394.353	.665	.335

UNSTABLE

75% Line Compensation.

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	3.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	55.621	.500	.500
4.500	60.121	0.000	1.000
13.500	73.621	.581	.419
17.269	90.890	1.211	-.211
15.365	106.256	1.163	-.163
13.897	120.152	1.048	-.048
13.467	133.619	.877	.123
14.573	148.192	.639	.361
17.825	166.017	.293	.707
24.190	190.207	-.215	1.215
35.123	225.330	-.862	1.862
51.878	277.207	-1.202	2.202
71.696	348.904	-.233	1.233

UNSTABLE

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	3.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	66.618	.500	.500
4.500	71.118	0.000	1.000
13.500	84.618	.542	.458
17.619	102.237	1.065	-.065
17.037	119.273	.950	.050
17.483	136.757	.746	.254
19.766	156.523	.434	.566
24.860	181.383	-.026	1.026
34.096	215.479	-.632	1.632
48.787	264.266	-1.084	2.084
67.543	331.810	-.515	1.515
81.175	412.985	.870	.130
82.346	495.331	.766	.234

UNSTABLE

80% Line Compensation.

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	2.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	43.353	.500	.500
4.500	47.853	0.000	1.000
13.500	61.353	.639	.361
16.747	78.101	1.425	-.425
12.919	91.019	1.456	-.456
8.811	99.830	1.435	-.435
4.893	104.724	1.409	-.409
1.214	105.937	1.401	-.401
-2.393	103.545	1.416	-.416

STABLE

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	2.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	55.621	.500	.500
4.500	60.121	0.000	1.000
13.500	73.621	.581	.419
17.269	90.890	1.211	-.211
15.365	106.256	1.163	-.163
13.897	120.152	1.048	-.048
13.467	133.619	.877	.123
14.573	148.192	.639	.361
17.825	166.017	.293	.707
24.190	190.207	-.215	1.215
35.123	225.330	-.862	1.862
51.878	277.207	-1.202	2.202
71.696	348.904	-.233	1.233

UNSTABLE

90% Line Compensation.

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	5.0

3 PHASE FAULT ON THE BUS NEAR THE STATION

DDN	DN	PE	PA
0.000	50.335	.500	.500
4.500	54.835	0.000	1.000
13.500	68.335	.604	.396
17.067	85.402	1.295	-.295
14.413	99.816	1.280	-.280
11.893	111.709	1.207	-.207
10.031	121.740	1.105	-.105
9.088	130.827	.983	.017
9.241	140.068	.834	.166
10.737	150.805	.634	.366
14.034	164.839	.340	.660
19.976	184.814	-.109	1.109
29.957	214.771	-.741	1.741

UNSTABLE

POWER(MW)	VOLTAGE(KV)	NO.OF LINES
15000.00	735.00	5.0

LINE TO LINE FAULT

DDN	DN	PE	PA
0.000	54.237	.500	.500
4.500	58.737	0.000	1.000
13.500	72.237	.587	.413
17.219	89.456	1.232	-.232
15.128	104.584	1.193	-.193
13.394	117.977	1.088	-.088
12.599	130.576	.936	.064
13.174	143.750	.729	.271
15.616	159.366	.434	.566
20.707	180.073	-.002	1.002
29.721	209.794	-.612	1.612
44.232	254.027	-1.185	2.185
63.895	317.922	-.826	1.826

UNSTABLE

70% Line Compensation.