SHUNT REACTIVE COMPENSATION OF EHV & UHV TRANSMISSION

- SURVEY OF THE STATE OF THE ART

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ABSTRACT

A broad overview of the problem areas associated with the planning and design of EHV and UHV transmission systems together with the various governing economic and technical criteria are given.

The application and problems of shunt reactive compensation of EHV and UHV long distance transmission lines in the optimal planning and operation of a power system is investigated.

The design process for determining the optimum sizing and location of (linear) shunt reactors on an EHV or UHV transmission network for voltage control is outlined taking into consideration various governing criteria.

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PART I

OVERVIEW

OVERVIEW

1. INTRODUCTION

In the last decade major advancements have been made in the transfer of bulk power over long distances, over 300 to 1000 miles, to provide:

a) Utilization of remotely located low cost energy sources such as hydro and mine-mouth thermal power, and

b) Interconnection of large power pools, particularly those with significant peak load diversity, for economic energy interchange and pooling of the generation reserve.

The transmission of bulk power over long distances inherently implies utilization of extra-high voltage (EHV, 330 kV-765 kV) and ultra-high voltage (UHV, 1000 kV and above) overhead transmission on the basis of economic considerations.

A greater utilization of transmission at these voltage levels will also be necessitated to carry the output from the very large generating plants, resulting from the continued trend of increase in size of generating units to provide reduced investment cost per kW installed.

EHV AC levels of 500 kV and 765 kV are already in operation. It is envisaged that UHV AC levels of 1000 to 1500 kV will be adopted by the late 1970's and be in service in the early 1980's as an overlay for some of the EHV networks to meet the projected load growths and overcome problems of obtaining rights-of-way for the multiplicity of lower voltage lines of equivalent capacity. The transmission capacity per line increases in slightly

1. Introduction (Cont'd)

greater proportion than the square of the voltage, the optimum line loading being related to its surge impedance loading.

Transmission of power by A.C. over long distances brings in many complications such as voltage regulation stability and line insulation. Bundle conductors are invariably used at these voltage levels to minimize corona and radio interference.

The major problems in the design of EHV and UHV equipment and transmission lines will be caused more by temporary power frequency over voltages in areas with moderate to high contamination and switching surges than by lightning over voltage which was the chief consideration at lower voltages.

It normally becomes necessary to utilize shunt reactors to absorb the excessive line charging current at light load conditions when line loading is below its surge impedance load, and thus limit the power frequency over-voltages in case of load rejection and on energizing lines. Application of shunt reactors with pre-insertion resistors in the line circuit breakers also reduces switching surges, which helps in effecting a lowering of the system insulation levels.

Automatic single-pole or three-pole reclosing circuit breakers with fast fault clearing times, series capacitor compensation, generator braking resistors and fast response high ceiling generator excitation systems may need to be utilized to improve

1. Introduction (Cont'd)

transient stability, and an excitation stabilizing signal used to improve the dynamic stability performance of the system.

Permanently connected shunt reactors increase the surge impedance and hence limit the capacity of the circuits; their removal and addition of shunt capacitors increases the load carrying capability of the lines.

Switching large banks of reactors or capacitors is a somewhat crude method to control the voltage. The two static reactive devices can be replaced by a synchronous condenser or by a static compensator composed of a saturable reactor, filters and shunt capacitors.

The recent development of the latter form of non-linear and controllable shunt reactors for reactive power compensation has led to the production of the English Electric's Triple-Trebler, the C.G.E.'s direct thyristor (SCR) controlled linear reactor, and the Brown Boveri's non-linear shunt reactor transformer.

The optimal solution of the combined voltage, stability and switching problem is the location, sizing and function of the reactive compensation in the system.

It is possible to improve the performance of a system by adding series capacitors, however an element in series, in general, represents a greater risk than a shunt element. More emphasis is

1. Introduction (Cont'd)

therefore placed on shunt reactive equipment to improve system performance.

The capability of high voltage direct current (HVDC) systems of the order of ± 400 kV to provide an economical high capacity long distance link and advantages of its asynchronous property has already been proven in operation. The role of HVDC at levels of the order of ± 800 kV will become apparent in the next few years as apparatus development continues and experience is gained.

In this report consideration is given only to EHV and UHV A.C. transmission systems and problems relating mainly to the selection of the proper shunt reactive compensation, for these systems.

2. ASPECTS OF A.C. TRANSMISSION SYSTEM PERFORMANCE

2.1 VOLTAGE CONTROL (Steady State)

One of the major problems in an EHV and UHV system is that of voltage control to provide good steady-state voltage regulation.

Under light load conditions the surplus amount of reactive power produced by the lines has to be either absorbed by the synchronous machines or compensated by shunt reactors. The reactive power compensation should be able to maintain steady-state voltage levels close to their nominal value under the various probable system operating conditions including varying system load levels; load rejection, line energization, and contingencies such as line, transformer or machine outage.

The profile of the line voltage, in other words the voltage levels along the length of the line, has to be considered and not just the terminal bus voltages.

2.2 STABILITY (Line Loading)

Fundamental to the system planning and design study is the concept of power angle or the angular spread in transmission line voltage as an indication of relative stability; systems having the same angular difference of its terminal voltages will have the same degree of stability.

The transmission system design must ensure that all generators remain in synchronism under steady-state and transient operating conditions.

The immediate consequence of a loss of synchronism is a partial loss of the feed that a part of the system was previously importing. The problem is often aggravated by the transfer of loads onto certain elements of the system which cannot support them and which drop out causing other losses of synchronism and resulting in a cascading effect.

Running out of synchronism also subjects synchronous machines to severe mech. stresses.

It is evident that if the new generation source is in a remote location then the transmission system associated with it must be based on stability considerations.

The total angular spread between the internal voltages of the existing generators (receiving end, say) and the new system (sending end, say) must be close to 90° (allowing for resistance

2.2 STABILITY (Line Loading) (Cont'd)

& saliency) at the steady-state stability limit. It follows that at this limit the angular spread across the transmission system should be the difference between the 90° and the sum of the voltage angles across the equivalent machine reactances at either ends of the transmission system. This angular spread across the transmission system at time of 110% of the maximum power transfer; i.e. when the output of the new generating station (sending end) is 10% above their rating, will provide a 10% margin to the steady-state stability limit which is a normally adopted design criterion. The phase angle across the line should normally not exceed 30° for stability reasons.

The equivalent machine reactance normally considered for steady-state conditions corresponds to the saturated synchronous reactance value, or, the arithmetic mean of the synchronous and transient reactances.

The stability of the transmission system is finally established by investigating the Dynamic Stability performance of the transmission system to a system disturbance such as load rejection, or to a series of system disturbances such as a system fault followed by switching out of the faulted system component and its restoration to service. It needs to be ensured that the system response is stable over and past the transient state that includes effects of machine excitation, governor action, machine saturation, machine damping, variation of frequency and voltage

2.2 STABILITY (Line Loading) (Cont'd)

dependent loads, and, relaying operation causing load shedding and changes in the network configuration.

The maximum allowable power angle across the EHV or UHV transmission line as determined from steady-state considerations may need to be revised from dynamic stability considerations.

In effect the reactance of the transmission line sets a limit on the maximum power which can be transmitted over it and thus high voltages are required to transmit large amounts of power over long distances.

2.2.1 Methods to improve stability

The main methods recommended for improvement of system stability are:

(1) Increasing the inertia of rotating sets, and, decreasing the transient reactance of the machines and the transformer leakage reactances. These means are, however limited by their costs.

(2) Use of damper windings for positive-sequence damping and negative-sequence braking.

(3) High speed over-excitation of alternators and synchronous condensers by means of controllers having very low inertia and rapid response exciters with a ceiling several times their rated voltage; the object being to prolong as long as possible maintenance of the rotor flux.

Methods of improve stability (Cont'd)

(4) Use of ultra-high speed circuit breakers and selective protection to effect the fastest possible elimination of the portion affected by a fault. Three-pole and single-pole automatic reclosure of transmission lines for transient faults greatly decreases the relative slip of the voltages at both ends of the line. This feature is most effective since transient faults constitute 70% to 90% of the total number of overhead line faults.

(5) Installation of intermediate switching stations in the case of two or several lines in parallel so as to limit the length of the section of the line to be tripped out in the case of a line fault.

(6) Installation of synchronous condensers or static reactive compensators in the intermediate stations to contribute to the maintenance of the voltage by the injection of reactive power during and after a fault.

(7) Decreasing the line reactance by use of series capacitors and bundled conductors.

(8) Use of generator braking resistors during system fault conditions to limit acceleration of the generator rotors.

2.3 INSULATION CO-ORDINATION AND LIMITATION OF OVER-VOLTAGES

2.3.1 Types of System Overvoltages

The overvoltages that can appear on the system can be classified into the following categories:

a) Atmospheric or Lightning Overvoltages;

b) Switching surges;

c) Normal power frequency and
Temporary overvoltages at or near power frequency - dynamic overvoltages.

The performance of insulation under category (a) is checked by a lightning impulse test.

The category (b) is checked by switching impulse test.

The category (c) is checked by dielectric tests at power frequency with the external insulation subject to atmospheric pollution and surface contamination.

2.3.1(a) Lightning Overvoltages

The transmission lines are generally protected against lightning for a desired performance by:

(a) Providing ground wires with adequate shielding angle to avoid direct strokes to the line conductors.

(b) Securing low tower-footing resistances within economic levels.

(c) Maintaining adequate clearances between the ground wires and the conductors, particularly at the mid-span, to prevent flash overs to the conductor.

2.3.1(b) Switching Surge Overvoltages

These overvoltages are generally of oscillatory nature and are caused by switching operations such as energizing and de-energizing of long lines on no-load, clearance of short circuits, interruption of low inductive currents such as transformer magnetizing currents, and load rejection. In addition, there are over-voltages on the sound phases when one phase has a fault to ground.

At EHV levels an important technical and economic consideration affecting the insulation design of the transmission lines and station equipment is the level of switching over-voltages.

At UHV levels the most serious problem is that of switching surges. The surge strength per unit length of long gaps and insulators decreases as the gap length is increased. This drooping curve indicates the upper limit of practical levels of UHV transmission.

However, the limitation of switching over voltages to 1.5 - 1.6 per-unit can be effected by the following techniques:

(i) Circuit breaker one step or multiple step closing resistors.

(ii) Controlled closing of circuit breaker poles; "point of wave switching".

(iii) Reduction of trapped charge on the lines by insertion of a non-linear resistor in the neutral of shunt reactors.

(iv) Surge diverters designed to operate for the small percentage of over voltages exceeding 1.5 → 1.6 pu..

If switching over-voltages are reduced to 1.5 pu. the internal dimension of a 1500 kV tower will only be 50% larger than those of a 765 kV tower.

2.3.1(c) Temporary Over-Voltages

A temporary over-voltage is an oscillatory phase-to-ground or phase-to-phase over-voltage of relatively long duration at a given location, which is undamped or only weakly damped in contrast to switching and lightning over-voltages which are usually highly or very highly damped and of short duration.

The temporary over-voltage pertinent to insulation of EHV and UHV AC systems in having a direct bearing on the selection or performance of surge diverters can be classified into three groups:

(i) power frequency over-voltages such as caused by energization of an open line or loss of load,

(ii) higher harmonic over-voltages such as caused by steady-state resonance due to the non-linear magnetizing inductance of the power transformer, or by transient resonance due to the switching of transformer terminated (but unloaded) lines, and

(iii) sub-harmonic over-voltages, characteristic for O/H lines with series compensation and caused for e.g. after the clearing of a fault by the series capacitor remaining

2.3.1(c) Temporary Over-Voltages (Cont'd)

connected between the source emf and a non-linear inductance (such as a shunt reactor) or a power transformer remaining connected to a source thru lines of high line charging.

Means for the limitation of Temporary Over-voltages

Group (i) - by installation of shunt compensation and proper relaying.

Group (ii) - by Relay protection, the third harmonic being practically eliminated by delta connected transformer windings.

Group (iii) - by shunting the series capacitor by a C.B. or by surge diverters.

2.3.2 Insulation Co-ordination - General

The notion of insulation co-ordination basically implies a correlation between the electrical withstand conditions of equipment, over voltage stresses on the system and characteristics of protective devices employed.

"Insulation co-ordination comprises the selection of the electric strength of equipment and its application, in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the characteristics of available protective devices, so as to reduce to an economically / operationally acceptable level the probability that the resulting voltage stresses imposed on the equipment will cause damage to equipment insulation or affect continuity of service."

2.3.2 Insulation Co-ordination - General (Cont'd)

This definition of insulation co-ordination - abstracted from IEC Publication 71 - sets forth the parameters of this problem: the electrical strength of the dielectric (external and internal insulation - air, porcelain, etc.), the voltage stresses and the margin of protection.

In the classical approach to insulation co-ordination the electrical stresses on the insulation and the electrical strength of the insulation is established and so matched as to provide a margin of protection.

However, as voltage levels increase, above 300 kV, it becomes more and more costly to provide the required margins of protection using conventional methods based on the characteristics of protective devices (such as lightning arresters, surge diverters, etc.) Thus the statistical approach must be introduced.

The statistical approach to insulation co-ordination takes into account the probabilistic nature of both the electrical stress and the electrical strength. It assumes that we can determine the probability distribution of the system overvoltages and also the distribution of the dielectric strength. The risk of failure is calculated from these distributions and thus the concept of system reliability itself assumes an integral part of the process of insulation co-ordination.

The insulation level of both the external and internal insulation

2.3.2 Insulation Co-ordination - General (Cont'd)

is defined as the statement of two values:

- the switching impulse withstand voltage, and
- the lightning impulse withstand voltage.

Particular attention must be paid to temporary over-voltages at UHV, where the prohabilistic method is applied to external insulation. For example, a temporary O/V of 1.5 pu may give as high a risk of failure as a switching O/V of 1.7 pu, because of the higher frequency of occurrence of the temporary over-voltages, in the form of long pulse trains.

2.3.3 Substation Insulation Design

In the choice of the insulation level for the substation equipment, the first considerations are that the more important equipment, namely the power transformer, in the stations is protected by suitably rated lightning arresters and that the internal over-voltages, including the switching surges, must not cause an interruption in the service. The value of the insulation level is based on the characteristics of the lightning arresters available which are invariably located immediately adjacent to the power transformers.The lowest insulation level is, therefore, for the power transformer and the remaining equipment is given insulation level slightly higher than that of the transformer.

The insulation co-ordination study in a substation is undertaken to determine:

2.3.3 Substation Insulation Design (Cont'd)

(i) Lightning arrester rating.

(ii) Transformer Basic Impulse (BIL) level.

(iii) Impulse levels for circuit breakers, disconnecting switches and bus supports.

(iv) Minimum electrical clearances.

2.3.4 Transmission Line Insulation Design

For EHV and UHV systems above 300 kV, the switching surge starts to become the determining factor for external insulation, vis a vis the line insulation level which in turn determines the insulator string length and other spacings that in turn affect the dimensioning of the towers and the width of the line route.

In general, the operating voltage determines the conductor size because of corona, radio noise and audible noise which may subsequently have been altered from considerations of losses or MVA capacity. The conductor size, however, also effects the tower dimensions in lieu of the corresponding mechanical loading stresses (wind and dead loads).

Thus the line insulation level and the line conductor size needs to be optimized in terms of total transmission cost and operating reliability of the EHV network.

The higher the operating voltage the greater the power transfer capability per mile on per square-foot of right-of-way, but higher also will be the resulting switching surge overvoltages.

2.3.4 Transmission Line Insulation Design (Cont'd)

Thus the emphasis is on reducing the switching overvoltages.

The power-frequency overvoltage will not greatly affect the tower dimensions except in areas of heavy pollution. Even here high-creep insulators may provide the necessary creepage distance within the dimensions determined from switching-surge considerations.

3 HIGH VOLTAGE PHENOMENA

3.1 Electrostatic Effects

Electrostatic effects near lines of 500 kV or more can result in hazardous conditions.

The remedy in most cases is adequate grounding, particularly for long fences and metallic structures near the lines.

Vechicle parking on the right-of-way should be prohibited, because tests have shown up to 1,700 Volts to ground on a parked automobile, and sufficient energy to ignite gasoline vapor.

Other remedial features are:

(i) raising the mid-span ground clearance to reduce voltage gradient at ground level.

(ii) Grounded shield wires under the line, at road and rail crossings to prevent induction of HV static charges on objects on the ground such as vechicles.

Tests results have shown that the voltage gradient at ground level should be kept below 15 kV/meter to avoid producing discomfort to people and animals near the line.

3.2 Corona

Corona discharges form at the surface of a transmission line conductor when the electric field intensity on the conductor surface causes a voltage gradient near the conductor which exceeds the breakdown strength of air. The breakdown of air in this region generates heat, light and radio interference, all manifestations of release of electromagnetic energy that results in power transmission loss, radio interference and audible noise.

The basic relationship describing Corona initiation on transmission line conductors is given by Peek's law:

$$E_0 = 30.0.\delta.m.\ (1 + 0.3/\sqrt{r})$$

where E_0 = Corona initiation (surface) gradient in kV peak/cm

r = conductor radius in cm

δ = relative air density

m = stranding and surface condition factor

The disruptive critical voltage at which Corona starts is given by,

$$V_0 = E_0\ r\ \log_e\left(\frac{s}{r}\right) \text{kV line-to-neutral}$$

where S = equivalent subconductor spacing in cm.

3.2 Corona (Cont'd)

The corona loss as given by Peterson's formula for fair weather per phase is:

$$P = \frac{3.37 \times 10^{-5}}{\left[\log_{10}\left(\frac{2s}{d}\right)\right]^2} \, f \, V^2 \, F \qquad \text{kW/mile of conductor}$$

where f = power frequency in hertz

V = effective line-to-ground voltage, kV

s = spacing between conductors

d = conductor diameter

F = function of $\left(\frac{V}{V_o}\right)$; where V_o is the Corona disruptive (starting) line-to-neutral voltage, kV

Corona losses may vary between 2 - 7% of the I^2R loss at Surge Impedance loading. However, Corona attenuates switching - surge voltage peaks which are frequently the controlling factor in EHV line insulation design.

3.3 Radio Noise, RI

In addition to the power loss resulting from Corona, there are high-frequency (radio frequency) components associated with the Corona discharge, which causes radio interference. Often radio noise sets a lower limit to the phase conductor diameter, dominates the design of bundled conductors, and creates special requirements for hardware and line stringing.

The spectral density of the RI generation surface density is given by:

$$SD\left[GD\right] = Kg\ 10^{C_1(G - G_o)}\ \text{amp}^2/\text{Hz.m}^2$$

where C_1 and Kg are empirical constants

G = conductor surface gradient

G_o = Peek's Corona-starting gradient

The spectral denisty of the generation density SD [GD] measures the mean square value of RI for per-unit values of band-width and surface area.

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

$$SD\left[G\right] = r\int_0^{2\pi}\left(1+K\ \frac{2r}{S}\cos\theta\right)^2 SD\left[GD\right]d\theta \quad \text{amp}^2/\text{Hz} - \text{m}$$

where r = conductor radius, meters

S = bundle spacing, meters

3.3 Radio Noise, R.I. (cont'd)

$$K = \begin{cases} 0, & \text{for single conductor per phase} \\ 1, & \text{for 2 conductors per phase} \\ \sqrt{3}, & \text{for 3 conductors per phase} \\ 3/\sqrt{2}, & \text{for 4 conductors per phase} \end{cases}$$

The partial discharges of the air (Corona) in the immediate vicinity of the conductor, which are the primary cause of transmission line noise, occur during both half-cycles of the applied voltage, but positive Corona is usually predominant at AM radio frequencies. Frequency modulated (FM) broadcast is inherently less sensitive to RI. A nominal acceptable reception level is given by a signal-to-noise ratio greater than 22 dB.

3.4 Audible Noise

At UHV levels, RI will probably not be a problem if the bundle configuration satisfies audible noise limits.

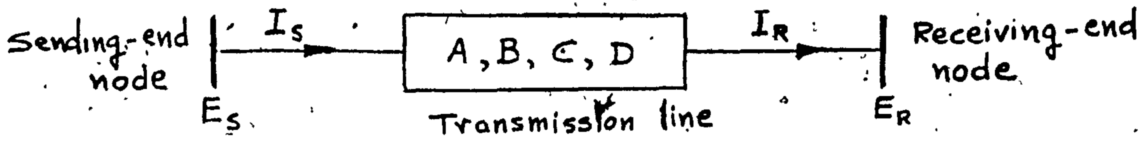
The principle conductor problem foreseen is audible noise. For AC lines up to 735 kV, a conductor bundle chosen on the basis of an acceptable RI level, produces audible noise which is usually below the acceptable level. At higher voltages, however, the audible noise may become the limiting factor in conductor selection.

4. GENERAL CONCEPTS RELATED TO EHV SYSTEMS

4.1 LOSSLESS LINE

The generalized representation of a long line in terms of the well known A, B, C, D constants is given by the relation:

$$\begin{pmatrix} E_s \\ I_s \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} E_R \\ I_R \end{pmatrix}$$



The A, B, C, D constants are defined by:

$$A = D = \cosh \gamma \ell$$

$$B = Z_o \sinh \gamma \ell$$

$$C = \sinh \frac{\gamma \ell}{Z_o}$$

Z_o is the characteristic impedance of the line $= \sqrt{\frac{z}{y}}$

and γ is the propogation constant for the line $= \sqrt{yz} = \alpha + j\beta$

where

z = the line impedance per unit length

y = the line susceptance per unit length

α = attenuation constant

β = phase constant

In case of the uncompensated Loss Less Line:

$$Z_o = \sqrt{\frac{L}{C}} = \sqrt{\frac{\text{Line Inductance}}{\text{Line Capacitance}}}$$

$$\gamma = j\omega\sqrt{LC} = j\beta$$

$$A = D = \cos \beta \ell$$

$$B = j Z_o \sin \beta \ell$$

$$C = j \frac{1}{Z_o} \sin \beta \ell$$

4.2 WAVE LENGTH

The wave length, λ, is the distance along the line between two points of a wave which differ in phase by 360° or 2π radians.

$$\lambda = \frac{2\pi}{\beta} \text{ miles,}$$

if β is in radians per mile.

At a frequency of 60 Hz a conventional overhead line is associated with a wave length,

$$\lambda \approx 3000 \text{ miles}$$

$$\left(= \frac{2\pi}{\omega\sqrt{LC}} \right)$$

i.e. a 750 miles long line is about one-quarter wave length and a 1500 miles long line is about one-half wave length.

4.3 SURGE - IMPEDANCE LOADING

Surge-impedance load (SIL) is the load that the line would carry were each phase terminated by a load impedance equal to $Z_o = \sqrt{\frac{L}{C}} = \sqrt{X_L X_c}$, where L is the series inductance and C the shunt capacitance per unit length of line.

Thus SIL = $V^2/Z_o = (kV_{LL})^2/Z_o$ MVA. It is approximately equal to that loading where the loss in reactive power due to the load current ($I^2 X_L$) is equal to the reactive power generated by the line capacitance (E^2/X_c).

The curve of Fig.1 , taken from the National Power Survey report prepared by the FPC, is representative of practice with respect to per unit surge-impedance loading of uncompensated lines as a function of line length.

The surge impedance load of a transmission line is a convenient measure of its transmission capability.

The surge impedance loading of an E.H.V. line, however, is not necessarily its economical 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 the surge impedance load is practically proportional to the square of the system voltage. On this basis the following relationship is established:

4.3 SURGE - IMPEDANCE LOADING (Cont'd)

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

4.4 CONCEPT OF SHORT CIRCUIT POWER

Higher fault level at the receiving end will lead to lower voltage swings; better voltage regulation, such as at time of switching of reactive elements on the systems.

As a rough rule of thumb the voltage fluctuation will be in the same proportion as the ratio of the switched reactance to the short circuit capability of the switched bus. For example, a 40 M.V.A. reactance switched from a bus with 1000 M.V.A. fault level will result in a voltage change of 4%.

When short-circuit power at the receiving end of the line is low compared with the power in transmission and more or less equal at certain points in the system, this complicates the protective system. Such is usually the case when EHV is used for carrying great quantities of power over long distances.

4.5 BUNDLED CONDUCTORS

The conductor size and bundling arrangement per phase affect tower loading as well as I^2R loss, corona loss, and radio influence levels.

The only practical method of limiting the conductor surface gradient, as the transmission voltage is increased, is by using bundle conductors; field intensity on conductor surface is reduced and with it - corona loss & radio interference.

Bundled conductors reduce line reactance and correspondingly increase the line surge-impedance loading.

Reduction of Line Reactance	Due to change from
20%	1 to 2 sub-conductors
27%	1 to 3 sub-conductors
30%	1 to 4 sub-conductors

4.6 NATURAL QUARTER-WAVE AND HALF-WAVE LINES

4.6.1 NATURAL QUARTER-WAVE LINE

A natural quarter-wave length conventional over-head line is about 750 miles long at a power frequency of 60 Hertz.

In this range long line theory predicts, inordinate voltage rises necessitating application of shunt reactors at intervals along the line. This can be seen by considering the uncompensated line to be lossless and studying it under the open-circuited condition and the normal energized condition.

Open-Circuit Condition:

$$\frac{E_{RO}}{E_S} = \frac{1}{A} = \frac{1}{\text{Cos}\,\frac{2\pi S}{\lambda}}$$

where E_S = sending-end voltage,

E_{RO} = open-circuit receiving-end voltage

For line length, $S = \lambda/4$; $E_{RO} \longrightarrow \infty$

and line charging requirements $Q_{SO} \longrightarrow \infty$

Both Terminals Energized at Nominal Voltage:

The voltage profile along the line under this condition will exhibit that the max. voltage variation occurs at the centre of the line. The magnitude of this voltage $E_{\text{mid-point}}$ depends upon the line length and displacement angle θ between the terminal voltages given by $\frac{E_{\text{mid-pt}}}{E_s} = \frac{\text{Cos}\,\theta/2}{\text{Cos}\,\frac{\pi S}{\lambda}}$

Both Terminals Energized at Nominal Voltage (Cont'd)

To achieve useful and practical operation of lines in the region of a quarter to a half wave length the necessity of shunt reactor application is emphazied by the preceding review of long line characteristics.

The Shunt branch, $y = \frac{A - 1}{B}$

This admittance can be completely compensated by connecting a shunt admittance at each terminal of the line with a value of: $y = \frac{1 - A}{B}$

For a lossless line less than one half-wave length, this compensating element is an inductive reactance, i.e. a shunt reactor. This compensation results in $A = 1$

$$\text{and } \frac{E_{RO}}{E_S} = A = 1$$

The reduction of line interval voltages (voltages at points between the line terminals) to practical levels can be accomplished by shunt reactors applied at one or more points between the line terminals. With the line divided into "N" equal sections and 100% reactor compensation at the terminals of each section ($y = \frac{1 - A}{B}$) the voltage magnitude at each reactor location will be equal to the sending end voltage under no-load and open-circuit conditions, the voltage in the center of each section will still be above the reactor terminal voltage

Both Terminals Energized at Nominal Voltage (Cont'd)

but will exhibit a resultant decrease as the transmission line is sub-divided into more equal sections, i.e. with increased "N". It is therefore possible to determine the appropriate number of line sections required to limit the highest interval line voltage to a specified value.

The effect of interval (distributed) shunt compensation on the real and reactive power transfer capabilities is given by

$$P_R = \frac{E_R E_S \operatorname{Sin} \theta}{B} = \frac{E_R E_S \operatorname{Sin} \theta}{Z_o \operatorname{Sin} \frac{2\pi S}{\lambda}}$$

$$Q_R = \frac{E_R E_S \operatorname{Cos} \theta - E_R^2 \operatorname{Cos} \frac{2\pi S}{\lambda}}{Z_o \quad \operatorname{Sin} \frac{2\pi S}{\lambda}}$$

For a completely shunt compensated N-section line, the received real and reactive power equations become:

$$P_R/P_O = \frac{E_R E_S \operatorname{Sin} \theta}{N \operatorname{Sin} \frac{2\pi S}{N\lambda}}$$

$$Q_R/Q_O = \frac{E_R E_S \operatorname{Cos} \theta - E_R^2}{N \operatorname{Sin} \frac{2\pi S}{N\lambda}}$$

where Po, Qo $= \frac{1}{Z_o}$, is the characteristic power.

4.6.2 NATURAL HALF-WAVE LINE

A natural half-wave length conventional over-head transmission line is about 1500 miles long at a power frequency of 60 Hz., or about 1800 miles long at 50 Hz..

Salient Features of a Half-Wave Line:

1. For a half-wave lossless line

   $A = D = -1, \quad B = C = 0$

   i.e. a half-wave line presents zero series impedance and zero shunt admittance.

2. $V_s = -V_R$; extremely stable end-voltages

   $I_s = -I_R$

3. $V_s I_s^* = V_R I_R^*$; no reactive power generation or absorption.

4. No Ferranti effect when line end is open and possibility of self-excitation is absent under light or no-load condition.

5. Mid-point voltage $\propto I_R$

   Mid-point current $\propto V_R$

Stability

Inherent advantage of half-wave line is the low angular separation between the sending-end and the receiving-end voltages under steady state conditions.

Synchronization:

For lines ⩾ half-wave length these must be energized from the sending-end and synchronism effected at the receiving-end since the angle of the sending-end machine will be leading the receiving-end lines by ⩾ 180°.

4.7 TUNED HALF-WAVE LINES

Tuned half-wave length power transmission lines constitute of artificial lengthening of relatively shorter lines to exploit the inherent advantages of a half-wave line.

This is accomplished by:

(1) Selection of operating frequency; which involves frequency changers hence is impractical.

(2) Parameter compensation; which involves the addition of tuning banks, Figs. 3 (a), (b) and (c), having -

  (a) series inductors and shunt capacitors, Pi and T type tuning banks.

or (b) shunt capacitors only along the line, capacitor type tuning banks.

The salient features and comparison of performance between the Pi, T, and capacitor type tuning banks are listed below:

(i) Line-end tuning banks experience over-voltages when loads greater than SIL are transmitted, which influences insulation level of the end-stations.

(ii) Capacitor-tuned line decreases Z_0 and hence increases SIL which provides higher transmission capacity compared with other types of tuned and natural half-wave lines.

(iii) A Pi or T-tuned line is more efficient than a capacitor tuned line but this is not significant considering (ii) above.

4.7 TUNED HALF-WAVE LINES

(iv) Power frequency over-voltages for line faults for Pi or T-tuned lines $\ll$ capacitor tuned lines.

(v) A capacitor-tuned line has a higher transient stability limit.

5. CRITERIA FOR A.C. TRANSMISSION SYSTEM PERFORMANCE

The planning of power transmission system development basically requires the establishment of the transmission voltage level, number of circuits and the conductor size. For this the criterion must first be set up on basis of which the alternative system confirgurations can be compared.

In general the following criteria has been adopted:

(i) Voltage Regulation

(a) ± 5% at all system buses under normal peak and light load conditions.

(b) ± 10% under abnormal conditions such as on line outage or load rejection.

(ii) Line Loading

(a) The angular spread between any two line terminations should be less than 30° for steady state stability considerations.

(b) There should be sufficient transmission capacity to allow for single contingency line outages anywhere in the system network.

(iii) Transient Stability

The test for transient stability is a Line-to-Ground fault on a single-circuit with high speed single-pole fault clearing and reclosure.

5. CRITERIA FOR A.C. TRANSMISSION SYSTEM PERFORMANCE (Cont'd)

(iv) Terminal Equipment Limitations

There should be no limitations by terminal equipment, such as circuit breaker fault interrupting capacities.

6. OUTLINE OF THE SYSTEM PLANNING PROCESS

6.1 Feasibility Studies

The first requirement in the planning of the synthesis of future systems is to establish the technical and economic feasibility of each of the basic conceptually established alternative long-range development patterns.

Feasibility is established in terms of:

(i) System voltage control

(ii) Stability

(iii) Cost of additions and modifications to the existing system in terms of the availability of money.

Hence, repeated steps of synthesis and analysis of the performance of the power system, are involved in establishing the broad conceptual and feasible alternatives of the future system development.

6.2 Preliminary Evaluation & Selection of Alternatives

The technically feasible alternative programs for system expansion are compared and evaluated primarily for:

(i) Reliability

(ii) Power-handling capacity.

(iii) Cost and relative economic merits.

Other considerations that may be given are:

- susceptibility of plan to variations in assumptions.
- adaptability of basic plan to changes due to unforseen developments.
- differences in right-of-way station site requirements.
- construction time requirements.
- maintenance needs.
- ease of operation.
- environmental considerations (such as air & water pollution restrictions).

6.3 Design Studies

Additional planning studies are now undertaken to modify and establish design details of the basic system development alternatives established by the preliminary conceptual & feasibility studies.

Line Design: Consideration is given to

(i) Insulation in lieu of
  - lightning performance
  - switching surge over-voltages
  - power frequency over-voltages

(ii) Conductor size & arrangement in lieu of
  - Corona
  - Radio & Audible Noise.

(iii) Tower Design.

The system is tested by load flow, stability, and short-circuit studies for all alternative design features which would affect its performance,

While the conceptual and feasibility studies of basic alternatives assure the best long range patterns of development, the design studies now adjust the details to assure optimum reliability and performance of the immediate system in light of the future program.

PART II

ANALYSIS OF INDUCTIVE SHUNT REACTIVE COMPENSATION APPLICATION AND PROBLEMS

ANALYSIS OF INDUCTIVE SHUNT REACTIVE COMPENSATION APPLICATION AND PROBLEMS

1. GENERAL APPLICATIONS

Shunt connected inductive reactors are a technically and economically sound means for controlling over-voltages and compensating line charging requirements.

The specific applications may be classified as follows:

(1) Control of capacitive line charging

- under light load conditions
- on energizing open-ended transmission line;
- counteracting the Ferranti effect.

(2) Limiting Over-voltages in case of:

- switching surges
- load rejection; dynamic power frequency over-voltages
- harmonics due to ferro-resonance such as transformer saturation.

2. LOCATION

Shunt Reactors may be located:

- on tertiary of E.H.V. transformers, or connected directly to the line, E.H.V. or L.V. bus.

2.1 Relative merits of E.H.V. Vs Tertiary Reactors

a) Size: E.H.V. reactors can have large ratings whereas the Tertiary connected reactors are limited to the size of the respective transformers.

b) Switching: the cost of E.H.V. circuit breaker will normally prohibit switching facilities on an E.H.V. reactor.

3. PROBLEMS

3.1 Stray-Flux

Unlike neutral grounding reactors, these operate at high flux densities at all times. This high strength magnetic field can cause circulating current and hysteresis loss in any magnetic material within the stray field, including re-inforcing steel in concrete.

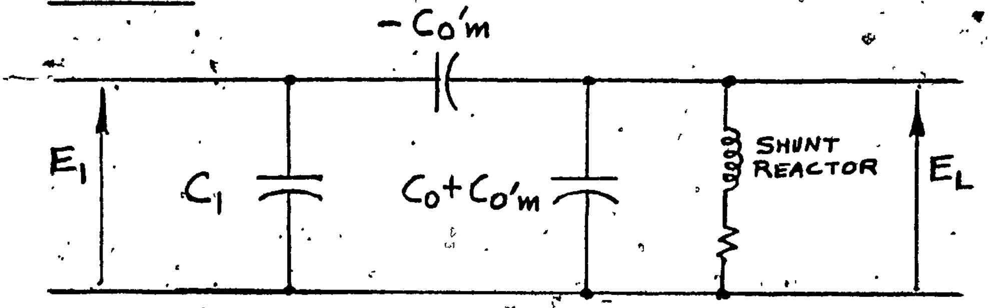
3.2 Switching Surges

The most severe switching surge on a transmission line will be generated by high speed re-closing that occurs before the energy trapped in the line capacitance has discharged. The trapped charge and the shunt reactor will set up alternating voltage of large magnitude within the time of normal high speed reclosure.

Circuit breakers with pre-insertion resistors- resistance inserted in the closing stroke-will sufficiently suppress the switching surges if reclosing is delayed until the A.C. voltage on the line has decayed to 90%.

For the Hydro-Quebec's 735 kV line use of closing resistors in the circuit breakers has enabled level of switching surges to be reduced to 2.0 p.u. from 2.1 p.u.. This in turn has made it possible to lower the line insulation level and consequently the number of insulators from 35 to 33 and the distance between conductors and metallic structures from 5.6 to 5.1 metres.

3.3 RESONANCE



E_1 = Phase to ground
voltage of energized circuit

E_L = Phase to ground voltage at the Shunt Reactor

C_1 = +ve seq. self-capacitance of energized circuit.

$C_0'm$ = mutual cap. between +ve seq. of the energized circuit
and zero seq. of de-energized circuit.

C_0 = Zero seq. self-cap. of de-energized circuit.

E.H.V. reactors connected to parallel lines either on the same right-of-way or the same towers can experience high voltages when the line to which they are connected is de-energized.

For E.H.V. lines $C_0/C_1 = 0.6 - 0.7$

Hence E.H.V. reactive compensation of 60-70% of positive seq. line charging MVA will be very close to a line-to-ground (or zero seq.) parallel resonance condition.

Very high resonant voltages can develop on an isolated E.H.V. circuit with line-to-ground shunt reactors built paralleling another E.H.V. or H.V. energized line. The difficulty stems from selecting reactors whose reactance matches line-charging reactance at or near power frequency, in which case the adjacent energized circuit merely provides excitation energy for the reactor compensated E.H.V. resonant path.

A single line-to-ground fault on the H.V. circuit will cause a sharp voltage rise on the isolated E.H.V. circuit.

Corrective Alternatives

a) Complete transposition of the circuits.

b) Unground the neutral of the E.H.V. reactor.

c) Insert a resistor or reactor between ground and neutral of the E.H.V. reactor.

3.4 Ferro-resonance/Harmonic Voltages

If voltages exceed the saturation voltage of transformers or reactors, they can introduce harmonic voltages which tend to peak at critical distances along the line, and can, if the reactors are non-linear cause ferro-resonance.

3.5 Limitation of Transmission Capacity

Shunt reactors when permanently connected, limit the capacity of the circuits, as they reduce the surge impedance loading.

The advantages to be obtained by incorporating switching of shunt capacitors and/or switching out of Reactor banks could lead to switching surge and load rejection problems. Switching of large banks of either reactors or capacitors is hence a rather crude method to control the voltage.

The fixed shunt reactive devices could be replaced by a synchronous condenser or even by a static compensator composed of a saturable reactor, filters and shunt capacitors.

The optimal solution of the combined voltage, stability and switching problems is more likely a combination of all the elements described above depending on their location and function in the system.

Field tests have demonstrated that circuit breaker insertion resistors and shunt reactors are the two most important means of reducing switching over-voltages.

In addition, inserting resistors in reactor neutrals before reclosing can reduce switching over-voltages to the level of initial energization.

4. STATIC REACTIVE ENERGY COMPENSATION

As opposed to the use of Synchronous Condensers for reactive energy compensation in a power system there is more interest in the use of relatively more economic static shunt reactive devices of the type described below, section 4.1 and 4.2.

4.1 The Non-Linear A.C. Saturable and Self Saturated Shunt Reactors

Unlike linear air-cored or gapped reactors the non-linear reactor has a closed magnetic core, similar to a transformer without its secondary winding.

The non-linear reactor can either be forced into saturation by energizing a d.c. winding on its magnetic core, the a.c. saturable reactor, or as in the case of the a.c. self saturated reactor, held in saturation by operation at a voltage corresponding to a flux density beyond the saturation level of the iron core.

The ideal voltage-current relationship for these two voltage control devices is shown in Figures 4 (a) and 4 (b).

Saturable reactors can in principle, provide the reactive power compensation required to control power frequency voltage rises, while in normal steady-state operation they do not absorb an an excessive amount of reactive power. Excessive reactive power consumption by a shunt reactor results in an increase in losses and the possible need for additional capacitive boosting.

Saturable and self saturated reactors in addition to reducing power frequency over voltages can also be instrumental in re-

4.1 The Non-Linear A.C. Saturable and Self Saturated Shunt Reactors (Cont'd)

ducing switching surge overvoltages for the following reasons:

a) they are instrumental in reducing the power frequency component of the switching transient.

b) they offer a finite impedance to travelling waves at the receiving end of an open-ended line thus lowering the reflection coefficient.

c) re-energization switching transients are substantially reduced since the reactors provide a path for the decay of the trapped charge.

d) shunt reactors allow a higher value of pre-insertion resistance and insertion time for multi-stage closing breakers. They also increase the overvoltage reducing effect of the pre-insertion resistors.

4.1.1 Harmonic Filtering & Damping

If a sinusoidal voltage is impressed at the terminals of a non-linear device, such as the saturated reactor, it draws a current from the supply which contains harmonics.

4.1.1 Harmonic Filtering & ~~Damping~~ (Cont'd)

The predominantly low and medium order harmonics can be eliminated for all balanced 3-phase systems by the use of polyphase multi-core reactors, such as the English Electric's Treble-Tripler saturated reactor.

The Shunt Reactor Transformer developed by Brown Boveri consists of a non-linear shunt reactor with a secondary delta-connected LV-winding.

With the LV-winding unloaded this provides the same static characteristic as a non-linear shunt reactor and due to the delta connection of the LV-winding the harmonic content of the primary current is reduced.

Oscillations at harmonics or sub-harmonics of power system frequency can occur if machines or transformers saturate in the presence of shunt or series capacitors. By the use of selective damping circuits this phenomenon can be prevented without producing appreciable power losses.

4.1.2 Major Applications

The major applications of the Non-Linear Reactor are as below.

In the series-connected mode:

4.1.2 Major Application (Cont'd)

(i) Short-circuit limiting couplings.

In the shunt-connected mode:

(i) Light flicker and voltage dip reduction in industrial installations.

(ii) Static frequency multiplication as used particularly for induction furnace supplies.

(iii) Power angle and voltage stabilization of A.C. transmission lines.

4.2 The Static Shunt Compensator

A static shunt compensator consisting of a combination of shunt non-linear reactors, shunt capacitors, harmonic damping and stabilizing filters yields a method of voltage stabilization which has an inherently high speed of response to system load changes and is also capable of giving the desired control for raising the stability limits of very long transmission lines with very little variation of line voltage between maximum and minimum transmitted load.

4.2.1 Voltage Stabilization

A typical form of a static shunt compensator used for voltage stabilization is shown in Fig. 5 (a), consisting of a saturated reactor and an associated shunt (boosting) capacitor together with a series (slope compensating) capacitor. Fig. 5 (b) gives the voltage-current characteristic of this device.

The capacitors introduced in series with the saturated reactor can reduce the apparent slope reactance of the saturated reactor to almost any arbitrary level and may even compensate the effect of external series reactances up to certain points in the system at which the maintenance of constant voltage is compatible with other considerations such as over load margins and the need to avoid harmonic instabilities. A saturated reactor with series capacitor can keep the voltage practically constant provided the frequency of the system remains constant.

4.2.2 Power Angle Stabilization

The ideal load for a long transmission line is its surge impedance load. The effect of adding an automatically adjusting voltage stabilizer can be expressed as a change of the average line surge impedance power to correspond to the transmitted power.

Fig. 6 illustrates an example of conditions to be expected on a very long EHV line with voltage stabilization at two intermediate points. The action of A.V.R.'s on the generators at each end of the line is assumed to maintain a constant voltage behind transient reactance.

Fig. 6 (b) gives the voltage/MVAR characteristics of the saturated reactor voltage stabilizers of the type described in section 4.2.1 above. The characteristics are with reference to the line voltage and a finite slope of the operating range of the characteristic, due to the leakage reactance of both the saturating reactor and the coupling transformer, is assumed.

Fig. 6 (c) shows the power-angle characteristic of the transmission line with shunt stabilization of this type. This is compared with the power-angle characteristic of a similar transmission line without stabilizers. There is an advantageous shift (to the right hand side) of the maximum of the power-angle curve defining the steady state stability limit.

4.2.2 Power Angle Stabilization (Cont'd)

Assuming that the stabilizers can hold the voltage constant irrespective of load the stability limit will be reached if the phase angle across any section of the line reaches 90° (neglecting the loss angle of the line).

Fig. 6 (d) illustrates the reactor phase angles of the line at the steady state power limit of transmission which (assuming sufficient capacitive MVAR capacity from the stabilizers) corresponds to an overall phase angle between voltage sources of about 175°. For this condition, the phase angle between the stabilizing stations is only about 45°, the power limit being reached when the phase angle between either voltage source and its adjacent stabilizing station becomes 65°.

Hence, the slope voltage variation at the stabilizers should be the minimum possible, and the choice of stabilizer distribution should as far as possible give equal maximum phase angles between voltage supported points.

4.3 Linear Vs Non-Linear Static Compensation

In the linear scheme, the natural shunt capacitance of the line is almost completely compensated by linear shunt reactors to prevent excessive over-voltages due to sudden loss of load. The series inductance of the line is partially compensated by series capacitors to keep the overall power angle down to an acceptable value.

In the non-linear scheme the saturated reactors absorb the capactive reactive power of the line at light loads, but release this reactive power to compensate the line voltage is achieved along the line and the power-angle curve for the non-linear scheme takes a linear form.

The difference in capacitive reactive power requirement in favour of the non-linear compensated line, can allow saturated reactors to be appreciably more expensive than linear reactors, and yet the non-linear scheme to be economically competitive.

With increased shunt capacitance an overall transient transmission angle of 180° would not represent a power-angle stability limit.

The non-linear scheme is therefore capable of extending the power capacity of A.C. transmission lines, beyond that of linear static compensation, into a region where, in the past, synchronous compensation has been recognized as the only conceivable solution.

4.4 Synchronous Condenser Vs. Non-Linear Static Compensator

In this application the non-linear static compensator has several advantages over synchronous compensation:

(i) Major portion of the reactive power range required for suitable compensation for A.C. transmission lines is lagging (inductive absorbing). Synchronous condenser designs inherently tends towards a reactive power range which is 2/3 leading (generating) and only 1/3 lagging (absorbing), which may be overcome by using a combination of linear shunt reactors and synchronous condensers.

(ii) Energising of lines is a matter of first switching in the reactors and then switching in the line. Whereas, for the Synchronous condenser running up and synchronizing procedures are required.

(iii) The internal reactance of the saturated reactor is only about half of that of the synchronous condenser (e.g. $X = 15\%$ for saturated reactor compared with, $X'_d = 30\%$ for synchronous condensers).

(iv) The internal (Leakage) reactance of the saturated reactor can be virtually compensated out (slope compensation) to give an overall rigid, flat voltage control.

(v) Just as a transformer the saturated reactor compensator does not require the degree of maintenance associated with synchronous condensers.

PART III

DESIGN PROCESS FOR PLANNING SHUNT REACTIVE REQUIREMENTS

DESIGN PROCESS FOR PLANNING SHUNT REACTIVE REQUIREMENTS

1. PRELIMINARY DESIGN PROCESS

Given the problem of planning and design of the extension of a power system to incorporate the transfer of bulk power over very long distances at EHV and UHV levels it is first necessary to establish the transmission voltage level, the number of required circuits and the network configuration alternatives. With the criterion of 30° angular spread across sections of the system with voltage support at either end, use can be made of the transmission capacity curves per Fig. 2 . The approximate transmission capability can also be found in terms of surge-impedance loading per Fig. 1 . From a co-relation of the above with the desired reliability criterion such as single contingency line or generator outage the transmission network configuration alternatives can be selected as a first approximation. This establishes a starting point for design; which can then be successively refined.

The flow chart for this preliminary selection of voltage levels, and the corresponding number of circuits is shown in Fig. 7 . This takes into account the right-of-way requirements and the capital cost per circuit in determining the minimum total cost alternatives.

The next phase in the design process for the final selection of conductor size and degree of shunt compensation is outlined in the flow chart given in Fig. 8.

1. PRELIMINARY DESIGN PROCESS (Cont'd)

The first step involves the insulation design of the proposed line.

The line insulation design is developed using a computer program which determines the number of insulators required per string and the minimum conductor-to-steel clearance, and calculates the expected flash over rates from switching-surge and dynamic over-voltage levels. The switching-surge over-voltages are determined with the help of a transient over-voltage computer programme. This computes the over-voltage on energization or re-energization of the transmission line in the system network utilizing the parameters of the proposed line.

The dynamic over-voltages are computed from load rejection studies.

Particular attention must be paid to temporary (dynamic) over-voltages at UHV, where the probabilistic method is applied to external insulation.

Lightning flash-over rates for specified values of structure footing resistance are also calculated.

The next step is to utilize a field strength programme which computes the surface voltage gradient for the given line conductor configuration and the corresponding Corona loss, radio interference and audible noise levels.

Next a parallel series of studies are performed. In one series the degree and planning of shunt compensation for acceptable performance of the system is determined for the different conductor

1. PRELIMINARY DESIGN PROCESS (Cont'd)

configurations and sizes. In the other parallel series studies are carried out for the tower requirements and associated costs.

From both the parallel series of studies the total annual charges are computed and a gradient method can be utilized for minimizing this total cost.

2. LINEAR PROGRAMMING FOR PLANNING REACTIVE REQUIREMENTS

The step for determining the optimum degree of shunt compensation in the complete design process as per the flow chart of Figure 7 can be based upon the use of sensitivity parameters and/or linear programming.

The optimization is carried out in terms of minimizing the requirements of the total installed reactive (MVAR) capacity and its allocation under both normal and contingency conditions postulated for the system under study to satisfy constrained system voltage conditions and other criteria for proper system performance.

The usual method of solving such a problem with simply the AC load flow digital computer program is that of "cut and try", a non-linear iterative technique dependant on engineering judgement.

This can be improved upon by the combined use of linear programming methods and the non-linear AC load flow programme computation as outlined in the flow chart per Fig. 8.

This method is based on the approximation that for relatively small changes, the change in bus voltage magnitude for a change in MVAR requirement is given by

$$\Delta E_i \cong \sum_j X_{ij} \Delta Q_j$$

2. LINEAR PROGRAMMING FOR PLANNING REACTIVE REQUIREMENTS (Cont'd)

where ΔEi is the per unit change in bus voltage magnitude at bus i;

Xij is the bus reactance matrix element;

Qj is the change in MVAR generation (or requirement) at bus j.

The objective function chosen for minimization is

$$\sum_j \Delta Q_j$$

subject to constraints

(i) $\Delta Ei \geqslant \sum_j X_{ij} \Delta Q_j$, for all network conditions

and

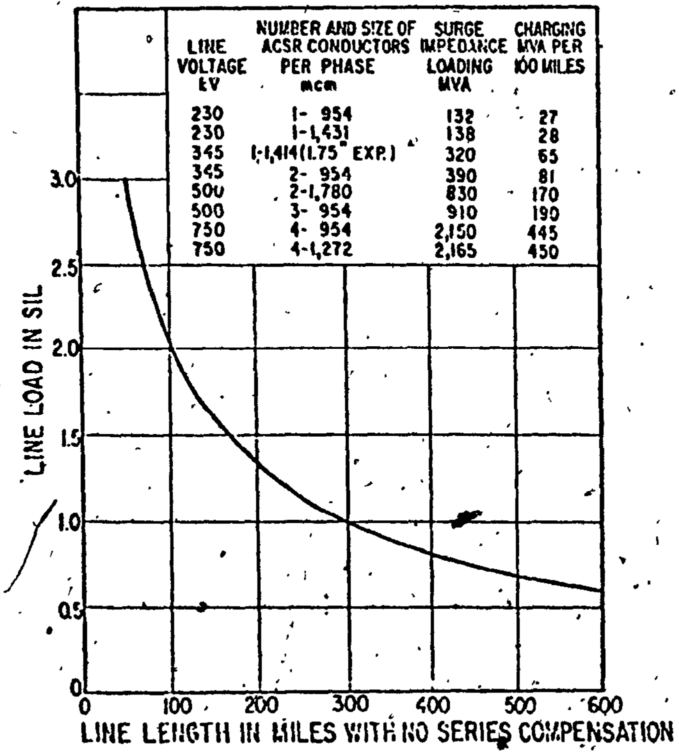
(ii) $|\Delta Qj| \geqslant 0$

where

i ranges over all buses of concern and

j ranges over all buses where MVAR reactive additions may be made.

FIGURES



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. 1 Transmission Line Capability in terms of Surge-Impedance Loading

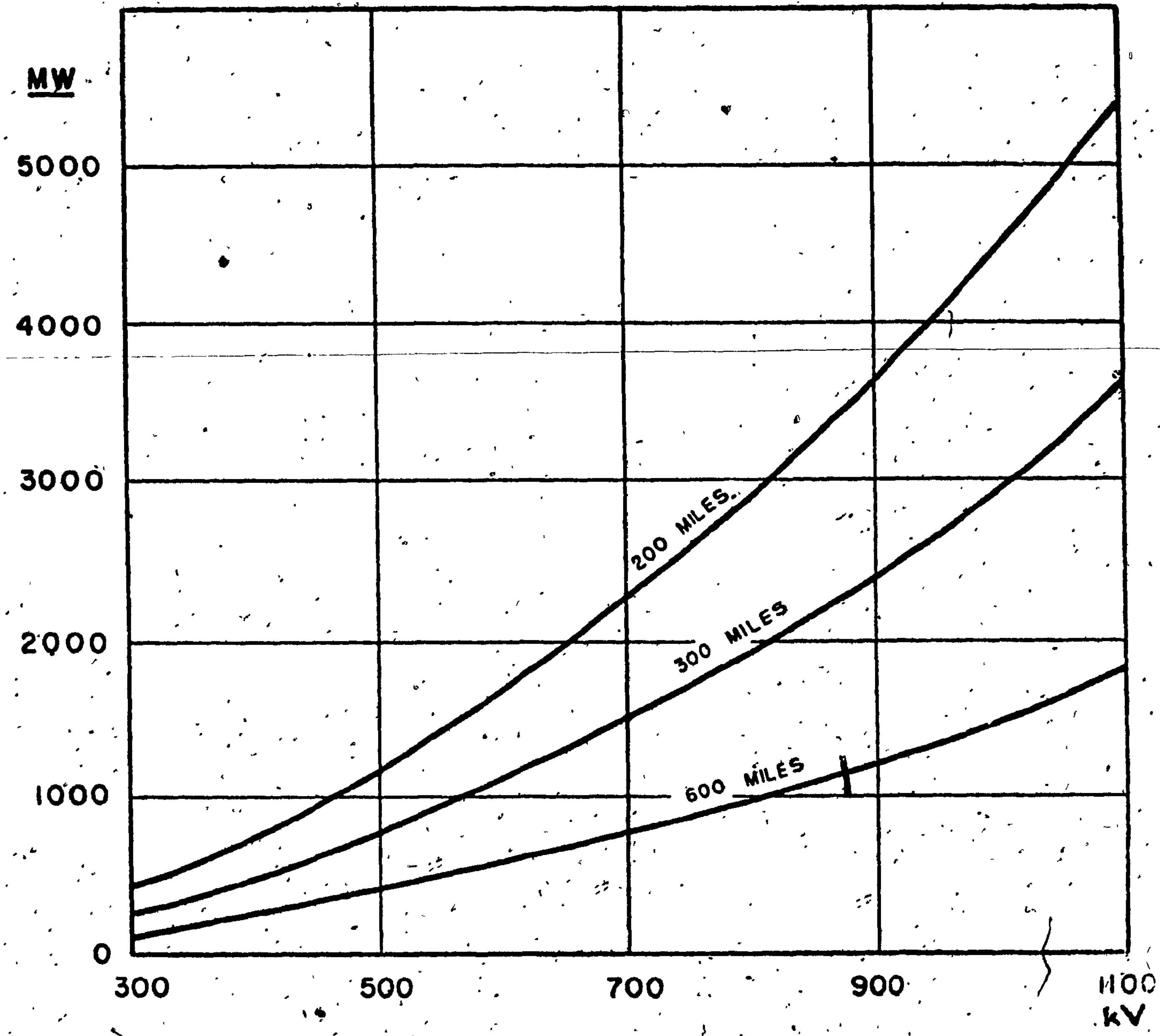
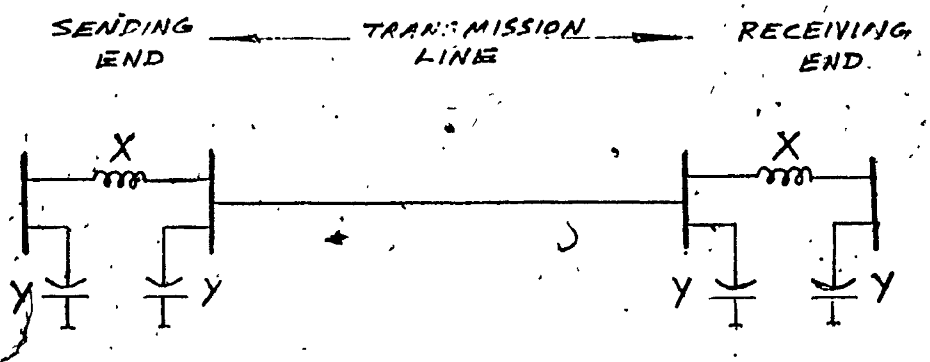
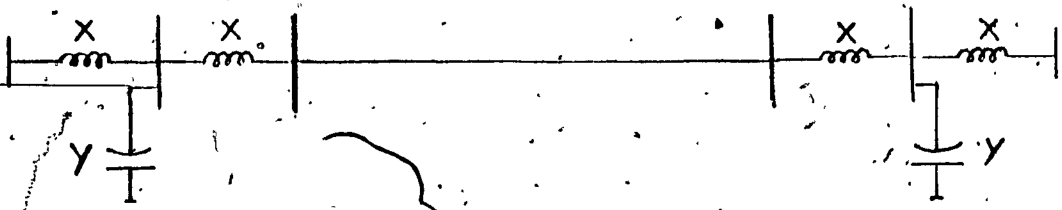


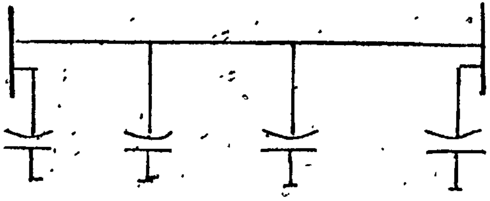
Fig. 2 Transmission Line Capability in terms of 30° Angular Spread



(a) Pi – TUNING BANKS



(b) T – TUNING BANKS



(c) CAPACITOR TUNING BANKS

Fig. 3 Tuned Half-Wave Line Parameter Compensation

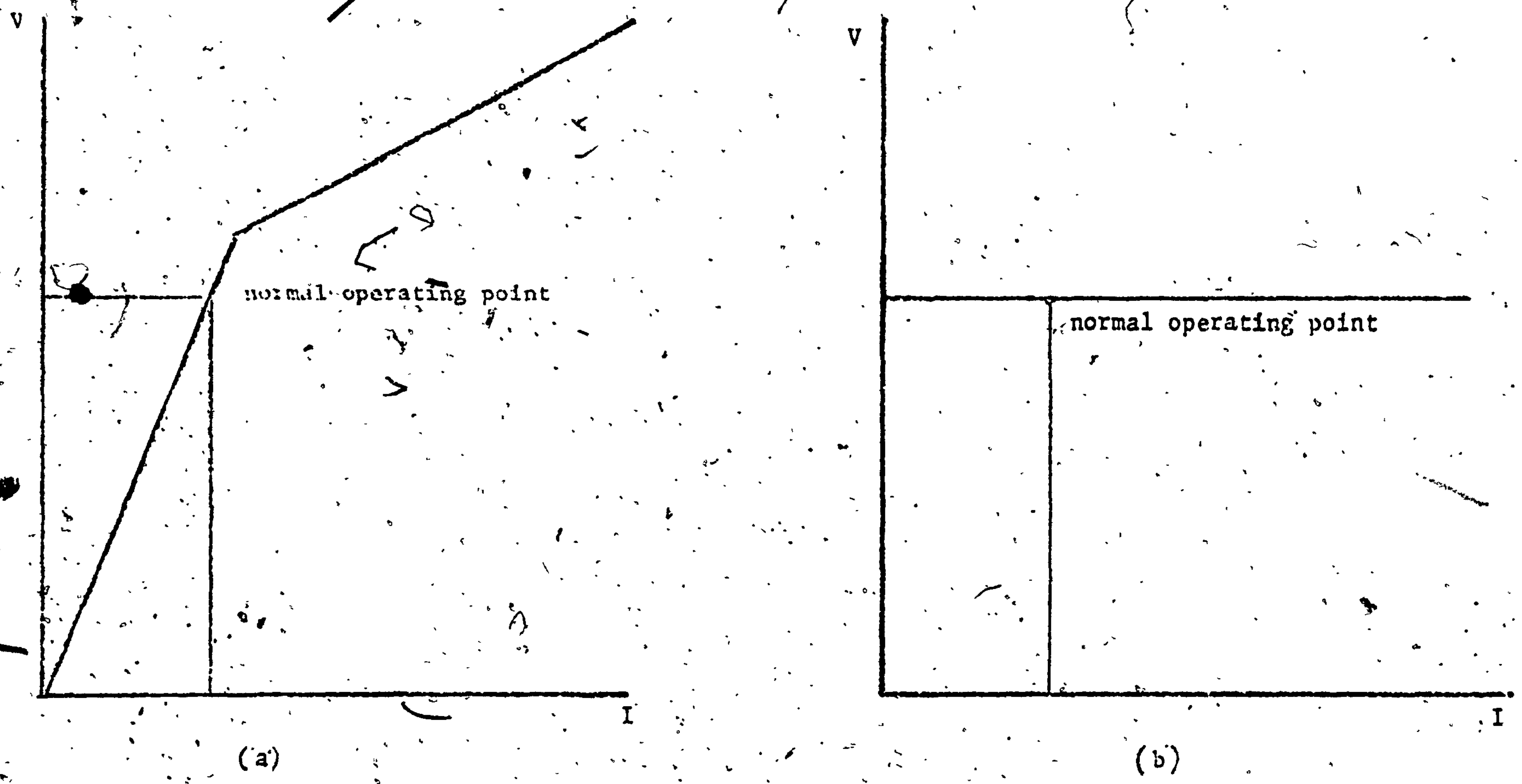


Figure 4 - Voltage current characteristics of
(a) an ideal saturable reactor
(b) an ideal saturated reactor

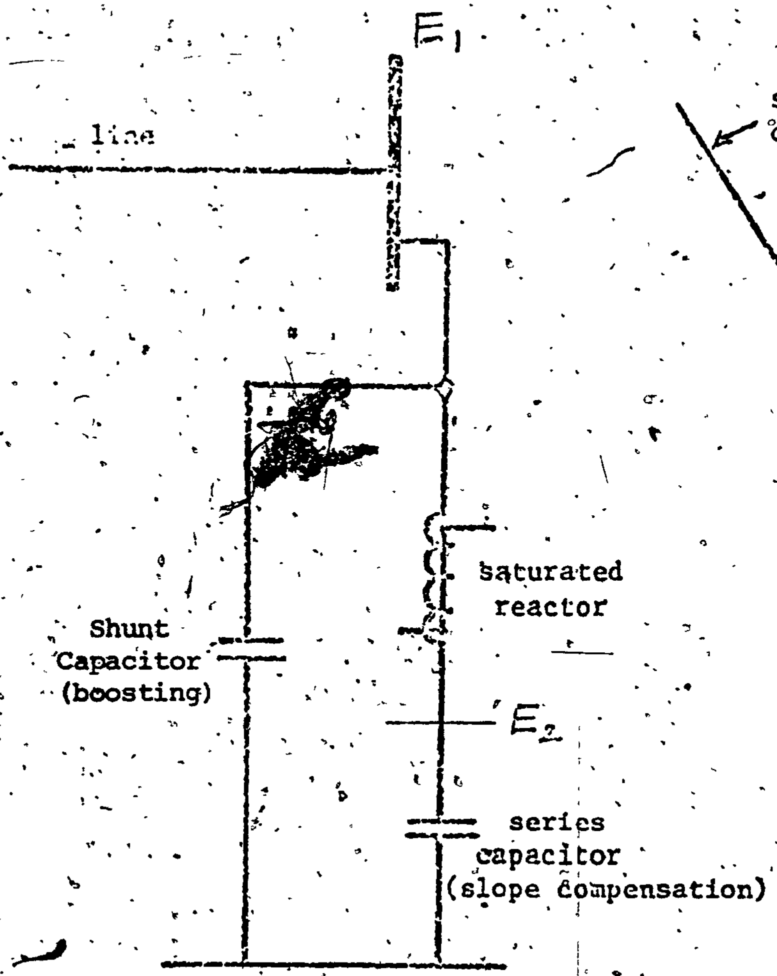


Figure 5(a) - Typical saturated reactor shunt stabilizer

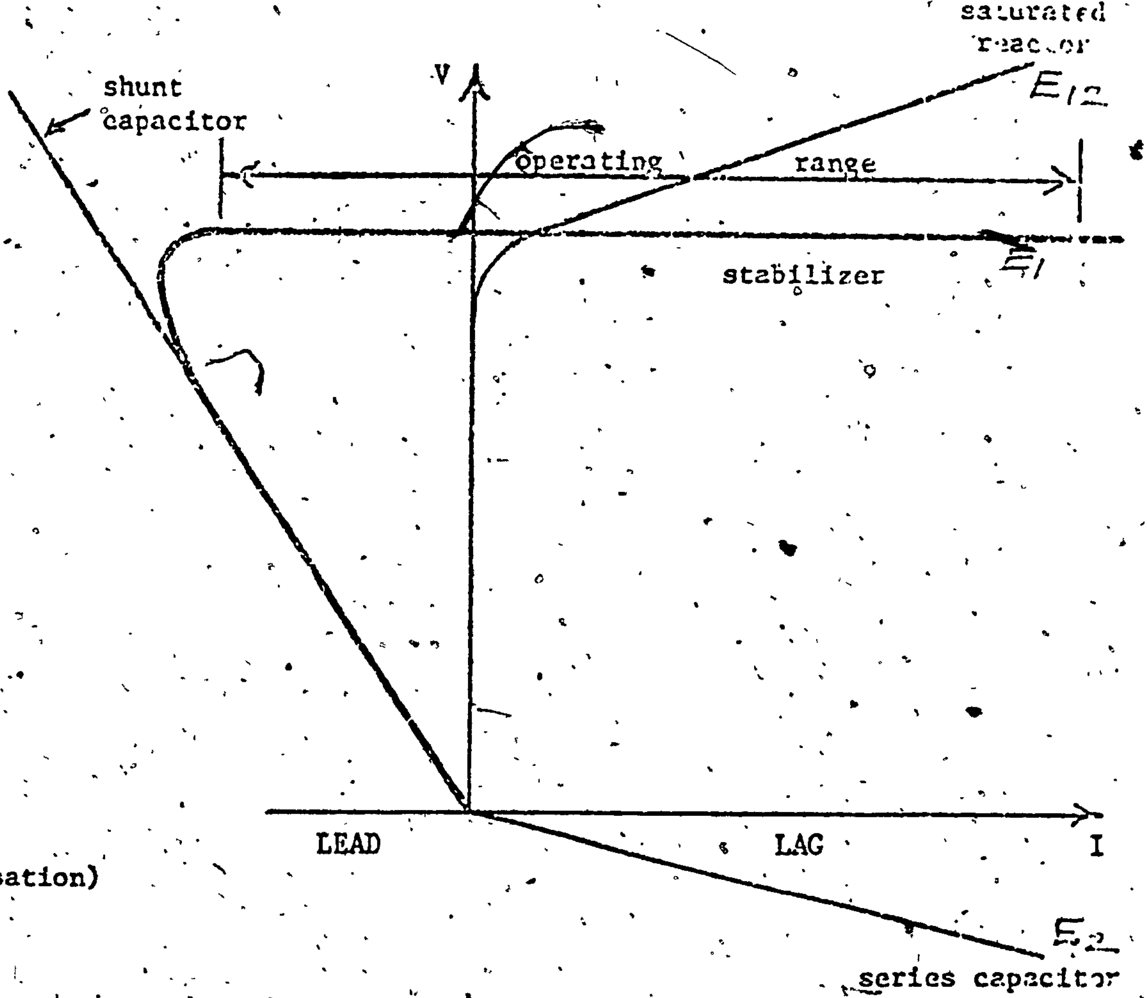
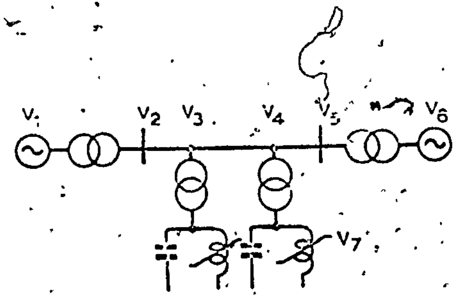
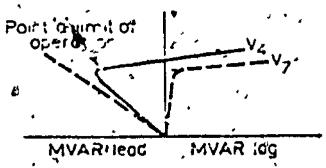


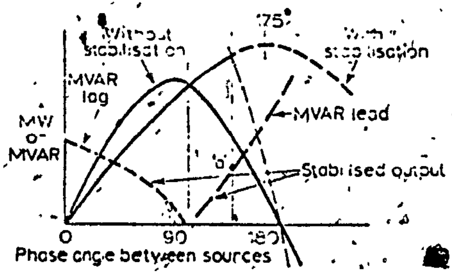
Figure 5(b) - Voltage-current characteristics of components of a saturated reactor shunt stabilizer



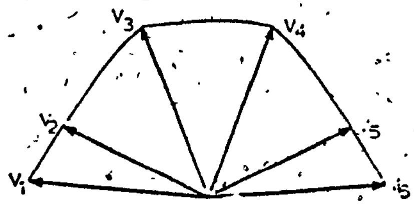
(a) Line with two intermediate stabilising stations



(b) Voltage stabiliser characteristics



(c) Power - Power Angle characteristics

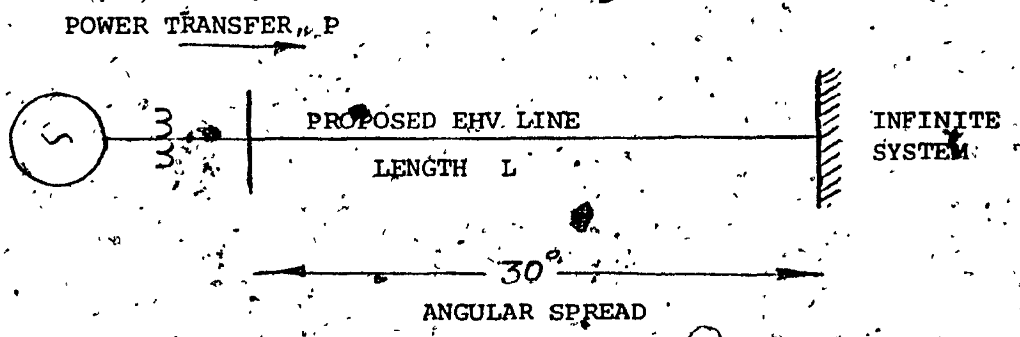


(d) Vector phase angle condition at steady-state power limit

Fig. 6 Characteristics of a long EHV line with voltage compensation

Fig. 7

FLOW CHART FOR PRELIMINARY SELECTION OF VOLTAGE LEVEL AND NUMBER OF CIRCUITS


POWER TRANSFER, P
PROPOSED EHV LINE
LENGTH L
INFINITE SYSTEM
30°
ANGULAR SPREAD

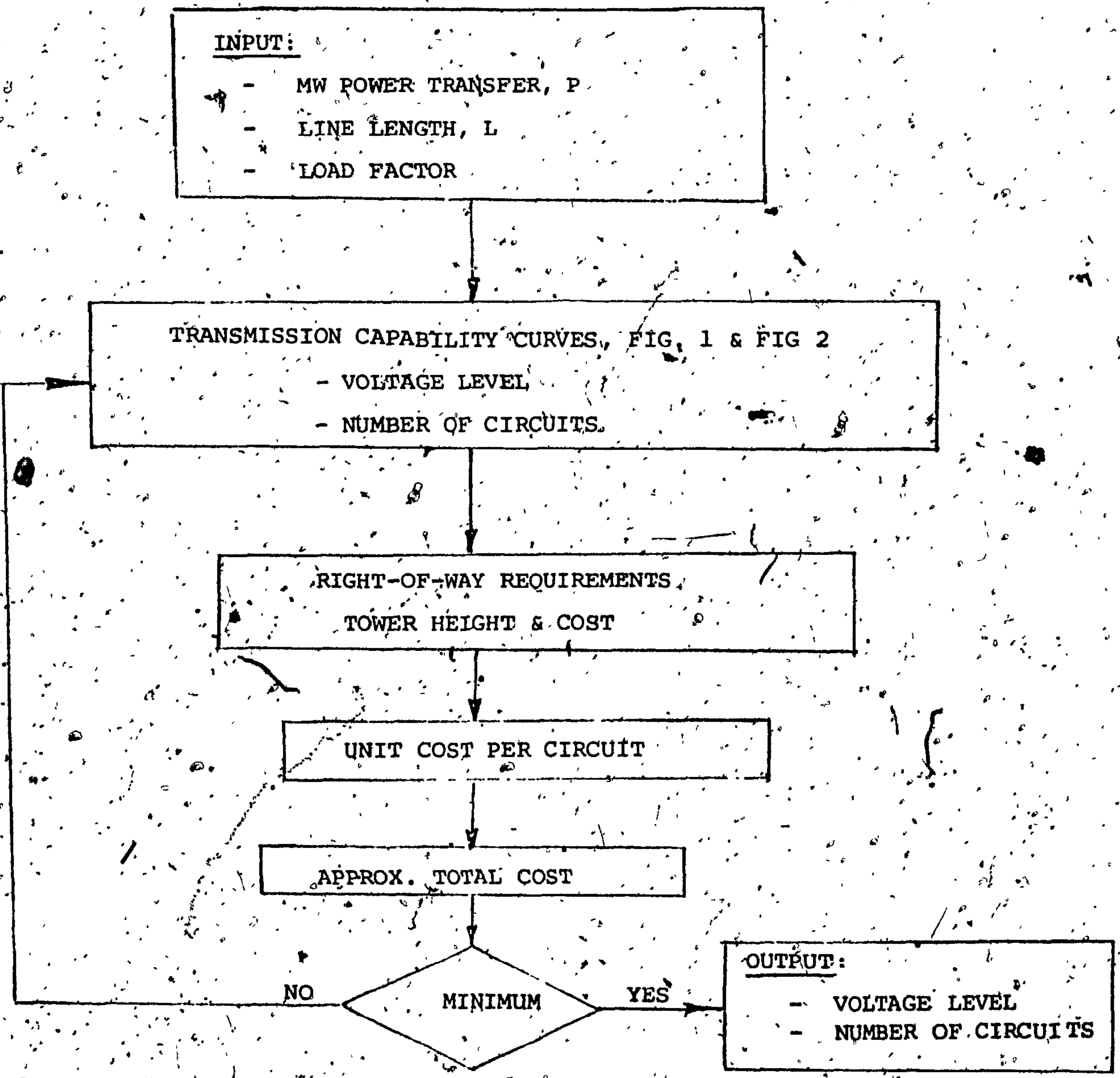

INPUT:
- MW POWER TRANSFER, P
- LINE LENGTH, L
- LOAD FACTOR
TRANSMISSION CAPABILITY CURVES, FIG. 1 & FIG 2
- VOLTAGE LEVEL
- NUMBER OF CIRCUITS
RIGHT-OF-WAY REQUIREMENTS
TOWER HEIGHT & COST
UNIT COST PER CIRCUIT
APPROX. TOTAL COST
MINIMUM
NO
YES
OUTPUT:
- VOLTAGE LEVEL
- NUMBER OF CIRCUITS

Fig. 8

FLOW CHART FOR FINAL SELECTION
OF CONDUCTOR SIZE AND DEGREE
OF SHUNT COMPENSATION

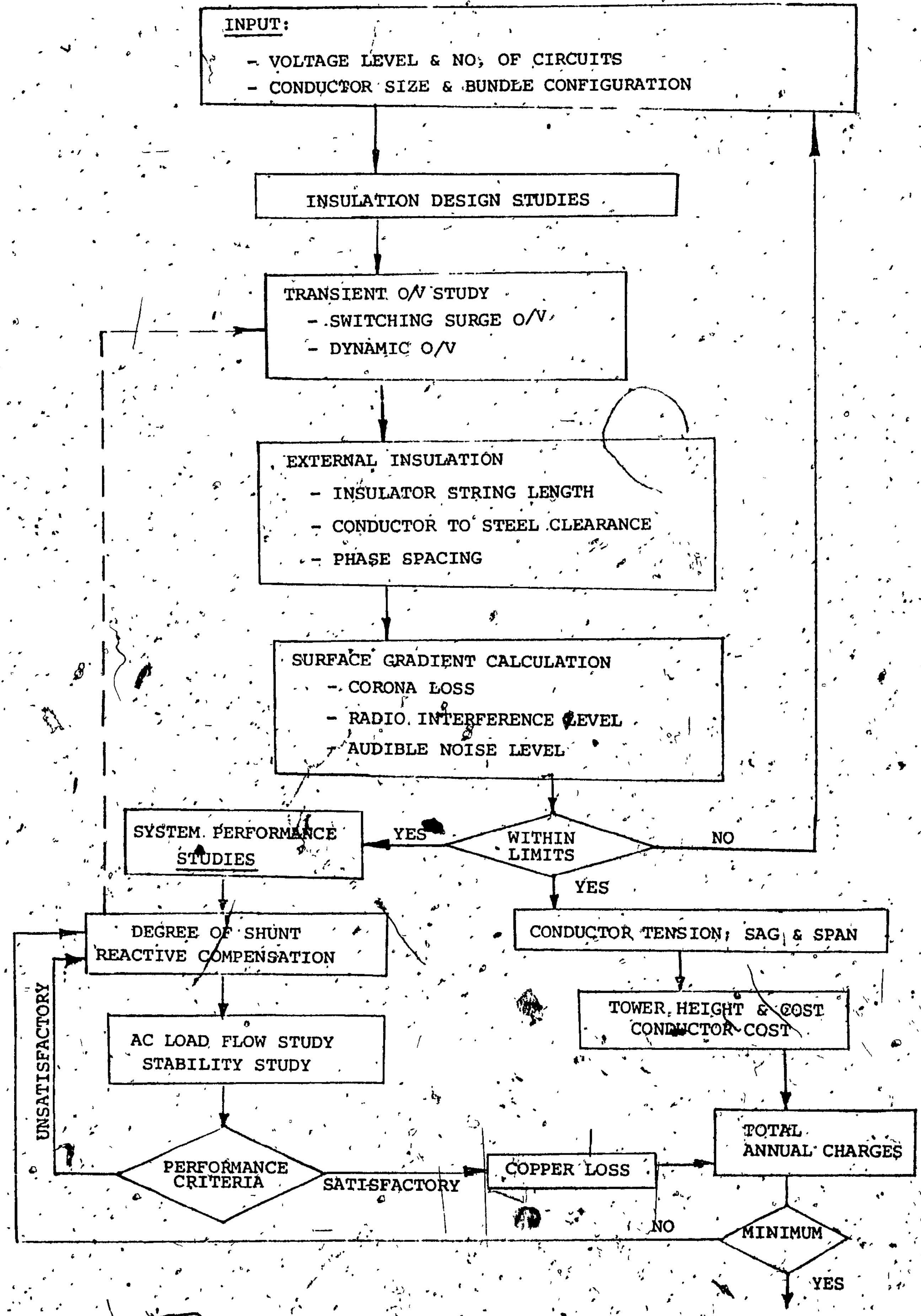
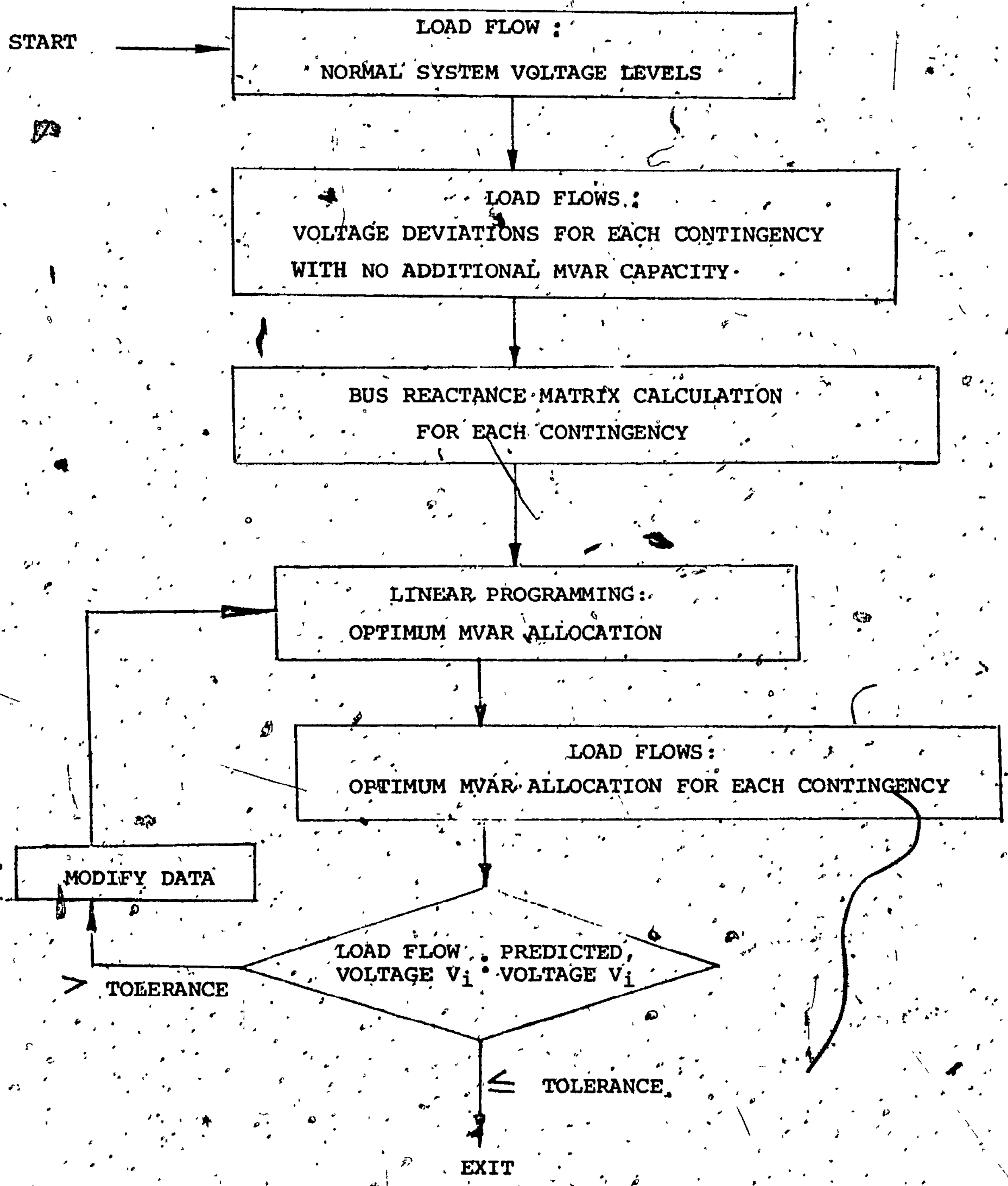

INPUT:
- VOLTAGE LEVEL & NO. OF CIRCUITS
- CONDUCTOR SIZE & BUNDLE CONFIGURATION
INSULATION DESIGN STUDIES
TRANSIENT O/V STUDY
- SWITCHING SURGE O/V
- DYNAMIC O/V
EXTERNAL INSULATION
- INSULATOR STRING LENGTH
- CONDUCTOR TO STEEL CLEARANCE
- PHASE SPACING
SURFACE GRADIENT CALCULATION
- CORONA LOSS
- RADIO INTERFERENCE LEVEL
- AUDIBLE NOISE LEVEL
WITHIN LIMITS
NO
YES
SYSTEM PERFORMANCE STUDIES
YES
CONDUCTOR TENSION, SAG & SPAN
TOWER HEIGHT & COST
CONDUCTOR COST
DEGREE OF SHUNT REACTIVE COMPENSATION
AC LOAD FLOW STUDY
STABILITY STUDY
UNSATISFACTORY
PERFORMANCE CRITERIA
SATISFACTORY
COPPER LOSS
TOTAL ANNUAL CHARGES
NO
MINIMUM
YES

Fig. 9

FLOW CHART FOR OPTIMUM
REACTIVE ALLOCATION


START
LOAD FLOW :
NORMAL SYSTEM VOLTAGE LEVELS
LOAD FLOWS :
VOLTAGE DEVIATIONS FOR EACH CONTINGENCY
WITH NO ADDITIONAL MVAR CAPACITY
BUS REACTANCE MATRIX CALCULATION
FOR EACH CONTINGENCY
LINEAR PROGRAMMING:
OPTIMUM MVAR ALLOCATION
LOAD FLOWS:
OPTIMUM MVAR ALLOCATION FOR EACH CONTINGENCY
MODIFY DATA
LOAD FLOW VOLTAGE V_i - PREDICTED VOLTAGE V_i
> TOLERANCE
≤ TOLERANCE
EXIT

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