STATIC VAR SYSTEMS

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ABSTRACT

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Utility system planners and operators have long recognized the value of controlling voltage and / or vars in providing quality service to their customers reliably and economically.

The Static Var System (SVS) is introduced as a relatively new apparatus for controlling voltage and var flow.

This paper provides a sufficient coverage of each phase of the subject through a review of existing literature in order to enable a good understanding of the basic principles for design of the static var systems. Some examples are given as they have been studied by the author for a real application of static var systems.

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CHAPTER I

INTRODUCTION TO STATIC VAR SYSTEMS

1.1 Historical Review

A considerable number of papers have been published in this area and the historical developments which have led to the techniques in use at the present tine are extremely interesting.

Although it is rather difficult to determine just when the first published material appeared, we can say that it was at least thirty five years ago.

Static var control systems first considered in 1964 (Akaki, Ethiopia), but did not become a commercial reality until 1969 (Kitne, Zambia).

Static var control systems up to 100 MVA have been installed to regulate transmission line.voltage in electric power systems.

For the James Bay project in Canada, a number of static var control projects are in study and another two are presently under installation (Rimouski by Canadian General Electric and Laurentides by Brown Boveri).

1.2 Introduction

Throughout the history of ac power transmission, it has been recognized that a major factor in the control and efficient operation of a power system is the ability to ensure optimum or near optimum voltage on the system. Over the years, many tools have been utilized in efforts to improve both the steady state and the transfer voltage control of power systems.

The problem associated with voltage control have been particularly prominent in North America where long distance transfer at EHV levels of bulk power has been common.

In Canada experience includes 500 and 735 kV, power up to 5,000 megawatts over distances of 600 miles. The James Bay project will extend this to 10,000 megawatts over 600 miles at 735 kV.

The unique nature of the Portage Mountain (British Columbia), Pinard-Hanmer (Ontario) and Churchill Falls (Québec- Newfoundland) systems, all EHV radial power transmission systems, and the upcoming James Bay project has resulted in the development of extensive Canadian experience in EHV equipment design and EHV system control.

1.3 The Nature of Voltage Variations

1.3.1 Long Term Variation

Long term reactively slow variations occur on power systems due to changing load and generation patterns during daily, or weekly and seasonal load cycles. The time involved in such deviation of voltage from system nominal values at both the transmission and distribution levels has permitted collective action utilizing conventional power system components i.e.;

- switched shunt capacitor banks
- switched shunt reactor banks
- changes in transformers taps
- switching of long EHV lines with substantial charging capacitance
- changes in generator regulator voltage set points and/or IX compensation settings

Modifications such as changing fixed taps on autotransformers and IX compensation settings are made manually, two or more times a year to track seasonal load changes.

To follow daily load cycles, capacitor and reactor banks and EHV lines may be switched in and out via supervisory control or by local automatic control based on a locally measured voltage.

Changing transformer taps is a simple and direct way to adjust system voltage when there is ample time to do so and the adjustement must not be made too frequently.

1.3.2 Rapid Random Variations, Flicker

Rapid variations in system voltage may occur particularly at the utilization level, due to rapidly varying loads (the most common being Arc furnaces or mines) which are large relative to the supply system. Such variations may be as much as 2-10% of the system short circuit capability and completely random in nature.

The number of such loads is increasing as thyristor drives become popular and the use and rating of Arc furnaces increase.

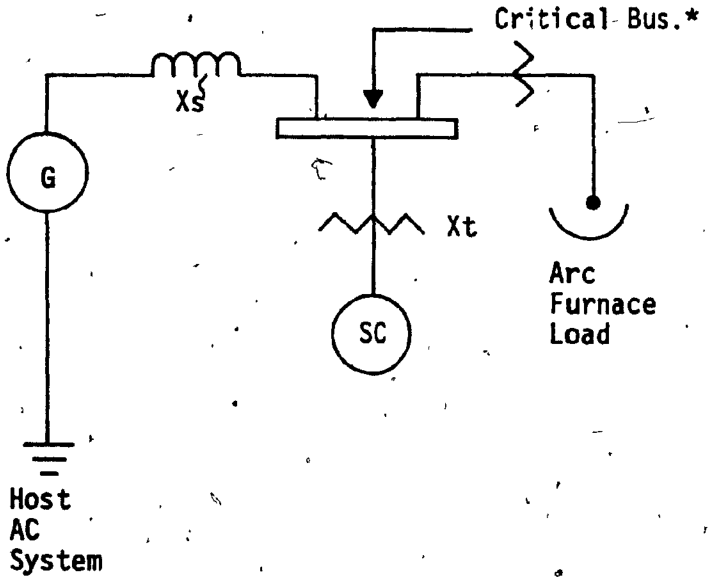
In a system with high enough fault level at the point at which these loads join the general network the fluctuations may not produce unacceptable voltage dips. But in smaller networks or in a case where new industry has been introduced into areas remote from the main inter-connectors, the system impedance may be too high.

The solution to such problems in the past has involved a combination of synchronous compensators anc buffer reactors.(115 At best, these solutions frequently resulted in limitations which result to furnace size and limitatiors being on operating procedure.

Synchronous compensator can be utilized as shown in fig. (1.1), to reduce the voltage flicker produced by Arc furnace loads. When an Arc furnace turns on, it apperars like a short circuit on the furnace transformer secondary. Voltage dips on the host system fig. (1.1), are reduced because of the synchronous compensator supplies some of the "fault" current drawn by the furnace.

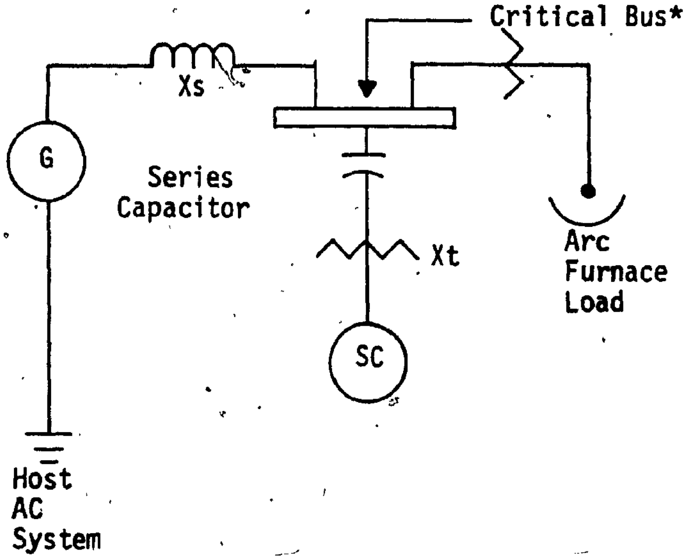
The lower the compensators reactance, the more current it can contribute thus less reactive current is drawn from the host system.

Series capacitors are sometimes used fig. (1.2), to reduce the compensator's effective reactance but a reduction of responsiveness results (because the capacitor is another storage element) and ferroresonance problems can result if care is not exercised.(Buffer reactors fig. (1.3), can be utilized also to further force a lesser current contribution from the host system. Extreme care must be exercised when choosing buffer reactors for such duty since the synchronous compensator may be dynamicall



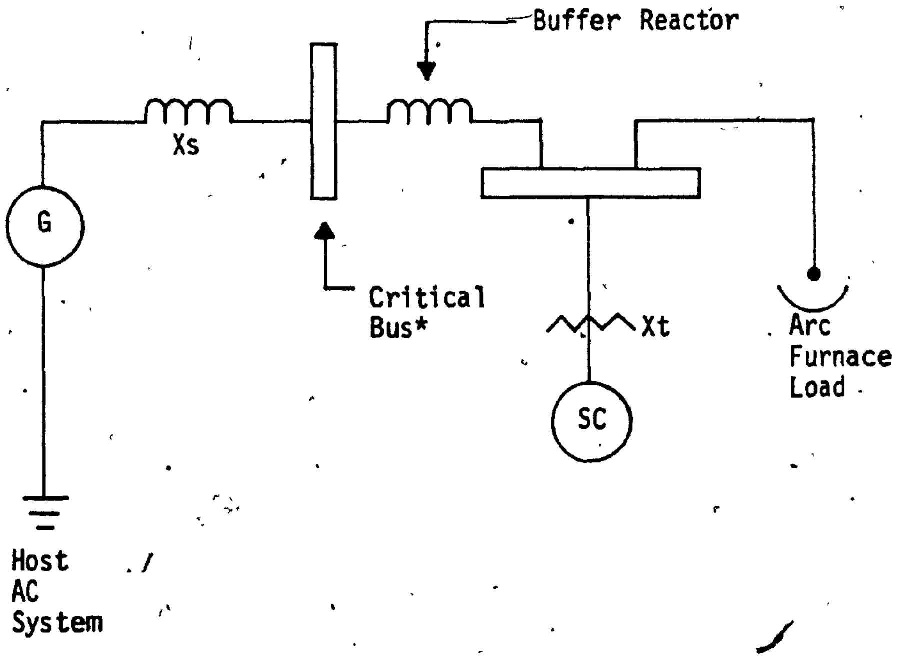
* Critical bus on which the voltage variations are to be reduced.

Fig. (1.1) SYNCHRONOUS COMPENSATOR FOR FLICKER CONTROL-
Basic Compensator Application



* Critical Bus on which the voltage variations are to be reduced.

Fig. (1.2) SYNCHRONOUS COMPENSATOR FOR FLICKER CONTROL-Series Capacitor



* Critical bus on which the voltage variations are to be reduced.

Fig. (1.3) SYNCHRONOUS COMPENSATOR FOR FLICKER CONTROL-Buffer Reactor unstable relative to the host ac system.

1.3.3 Variation Due to Load, Line, or Generation Loss

During transmission system disturbances resulting from live faults, loss of load, or generation line switching voltage, decreases may seriously limit the system power transfer capability. Such limitations are more common on long radial systems with a minimum of active voltage support between generation and load. Systems which fit this description include the James Bay project in Canada and the Itaipu system in Brazil, although on smaller systems synchronous compensators have been used with some success, extensive system studies(72) indicate that little, if any, improvement can be expected on large radial systems and under many conditions the system stability limits may actually decrease.

1.4 Voltage Requirements for Electric Power Systems

Each of the voltage variation types mentioned above effect the utility customer or the utility system in a different manner.

Long term voltage variations, although easily corrected by conventional equipment may, if allowed to result for long periods, result in inefficient operations and reduced life for plant equipments.

Random, rapid variations at the utilization level may have serious consequences with respect to electronic process control systems with possible loss of production. In addition, the number of complaints with respect to lamp flicker has, in the past, justified considerable expense on the part of many utilities to reduce or eliminate such voltage variations.

Variations due to load, line or generation loss may be of such magnitude as to result in system instability followed by a system shut-down. Such shut-downs invariably are costly to both customer and utility, system design is normally such as to minimize the chance of such a happening where continous variation or very fast response is required then, a compensator must be used.

1.5 Stabilizing the Bulk Power Network

Voltage support and var compensation schemes are used to maintain stable system performance in the face of line, generator and apparatus outages.

For economic transmission the voltage must be maintained close to the maximum design voltage at heavy load, and prevented from rising too much on light load. In particular the rapid and excessive voltage due to ferranti effect (127) on loss of load must be prevented.

This requires:

a) var to be fed into the line at heavy load

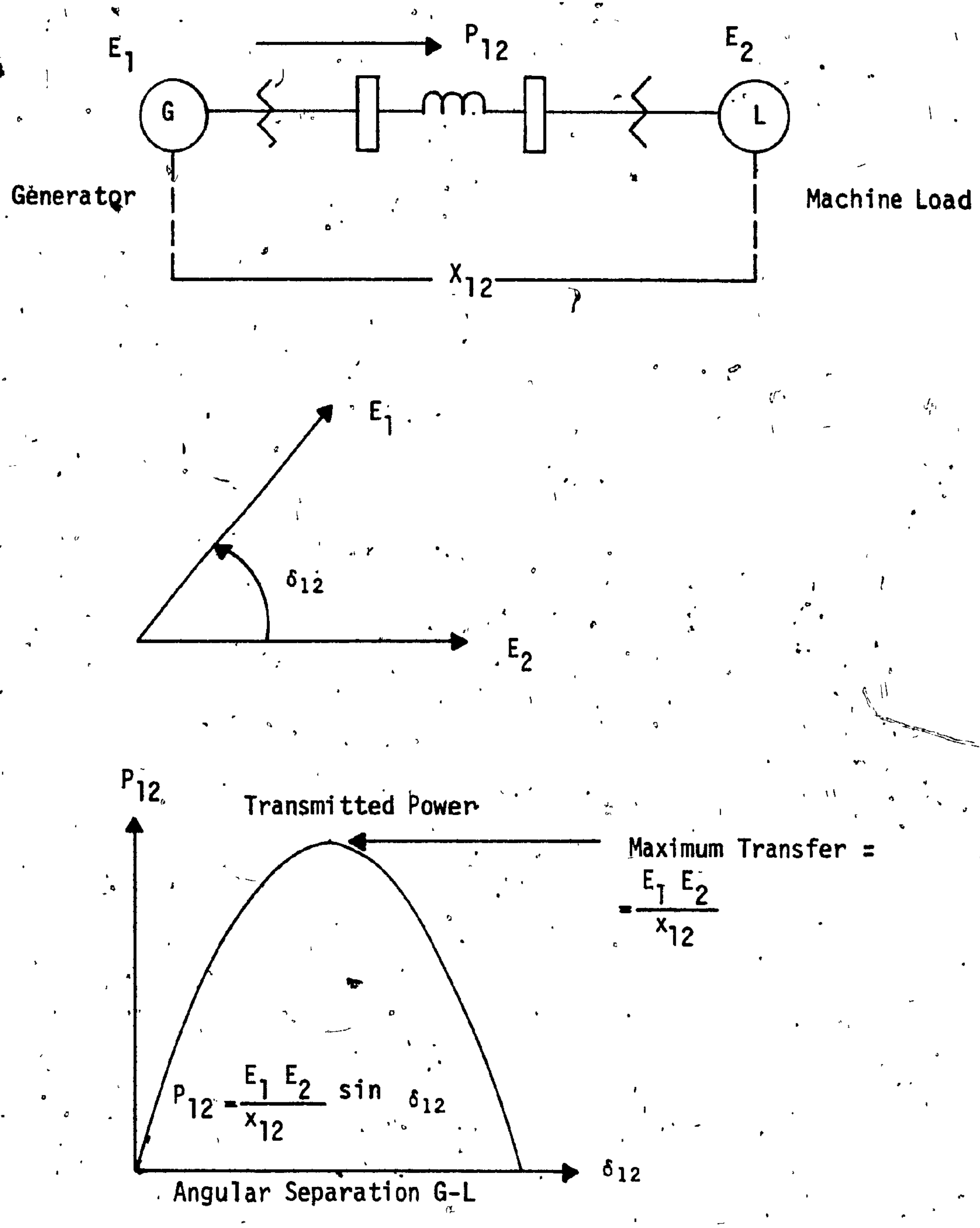
b) var to be absorbed from the line at light load

c) a very rapid and large increase in var absorbtion after loss of load

d) practically instantaneous response to system changes

e) a continous voltage control (step control can give instability)

Two basic schemes are utilized to insure the network's transport capability under normal steady state and transient system condition faults. The first is to maintain a suitably low impedance in the path between generator and load, fig. (1.4), shows how impedance relates to power transport capability.



No intermediate voltage support.

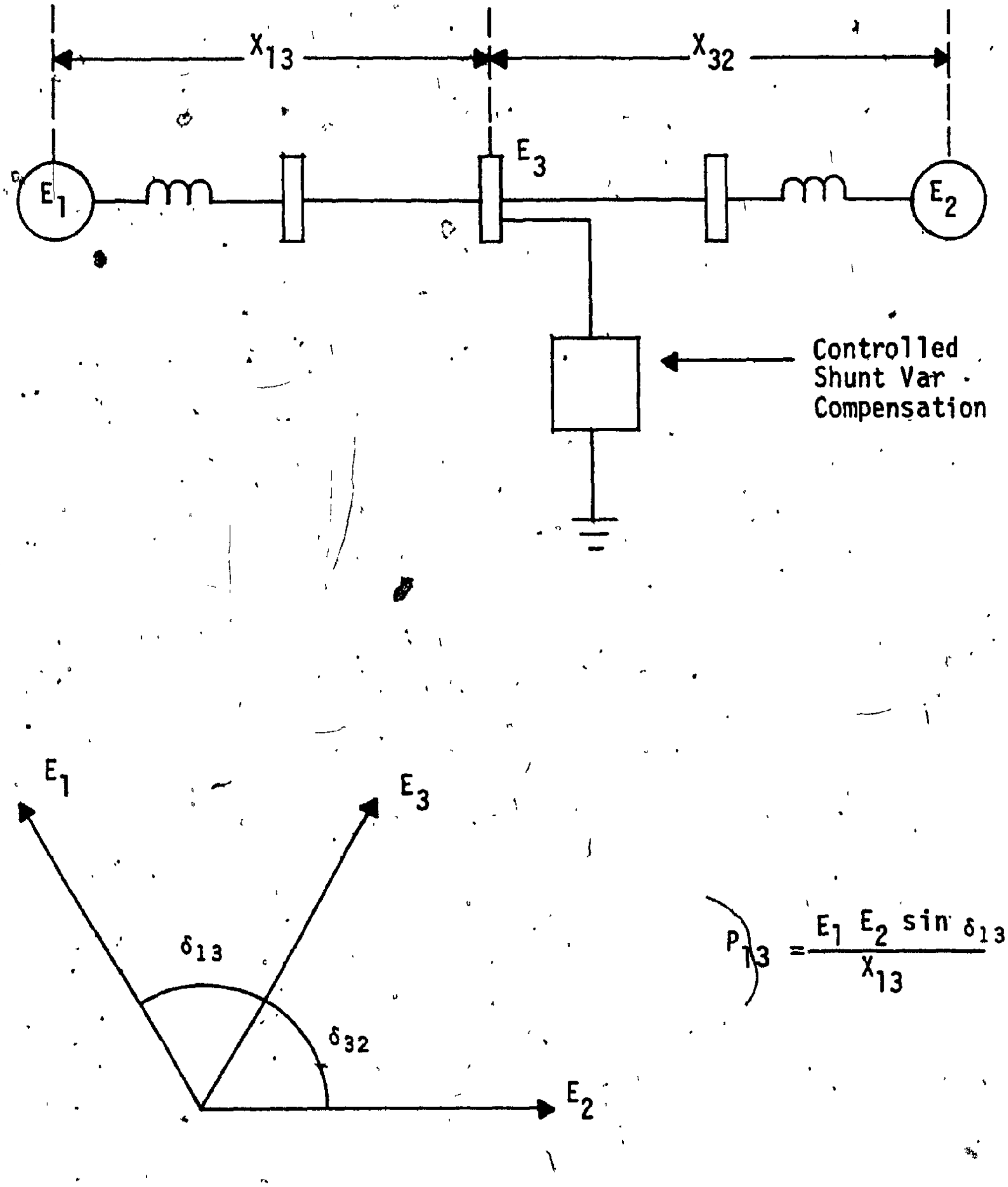
Fig. (1.4) P_{12} - POWER TRANSFER CAPACITY

The maximum power capacity is seen to be proportional to the produce [(129)] of voltage at end-points of the flow path. If the voltage at either end is reduced, the capacity is reduced. Similarly if additional voltage support is utilized at intermediate locations, the power transfer capacity can also increase.

One of the limits on the power transfer capability of a line is the transmission angle i.e., the angle between the voltage reactors and the two ends. This angle is proportional to power x distance and series capacitors, by reducing the effective length of the line, reduce the transmission angle. They cannot assist in controlling voltage. Shunt connected compensators, on the other hand, provide voltage control at intermediate points on the line and, as shown in fig. (1.5), for a simple two section line, increase the power transfer by enabling each line to be considered separately.

The second basic means for maintaining steady state stability is to maintain the voltage tight control at strategic points along the power transport path for long lines or large networks with dominantly unidirectional power flow patterns.

In order to maintain a good voltage profile and to keep system losses to a minimum, var compensation equipment must be located throughout the system and its type must be related to



$$P_{13} = \frac{E_1\ E_2 \sin \delta_{13}}{X_{13}}$$

$$P_{32} = \frac{E_3\ E_2 \sin \delta_{32}}{X_{32}}$$

Fig. (1.5) ONE INTERMEDIATE VOLTAGE SUPPORT SYSTEM.

network requirements in terms of magnitude and the speed of load variations.

Where voltage steps are unacceptable, where partial load rejection is possible, or where transient stability is critical, a continously variable type of compensation is required. If this continous control of voltage or vars cannot be supplied by generation on those key locations, synchronous compensators or their functional equivalent must be utilized.

1.6 Var Control Equipment and Characterisitics

There is nothing wrong with the time honored approach of using switched shunt capacitors to provide the desired amount of leading vars. Likewise switched shunt reactors are equally good for providing lagging vars when this is what the system requires. These may be done either at EHV levels directly or coupled through transformer tertiaries.

If var control equipment can be located near a point in the power system where the load power factor is significantly less than unity such a var supply has the added advantage of decreasing current and power losses in other portions of the system. Also for high transmission line loading, vars must be supplied at the receiving end of the lines.

1.7. Synchronous Compensators

Synchronous compensators have been successfully employed in controlling utility system voltage for rapidly fluctuating Arc furnace loads and also for controlling system power factor. These rotating machines require substantial foundations, as well as a significant amount of starting and protective equipment and maintenance. While their average response time is relatively slow, in the order of a second, they can sustain short time overloads and for transient power swings they have approximately the effect of holding a constant voltage behind transient reactance.

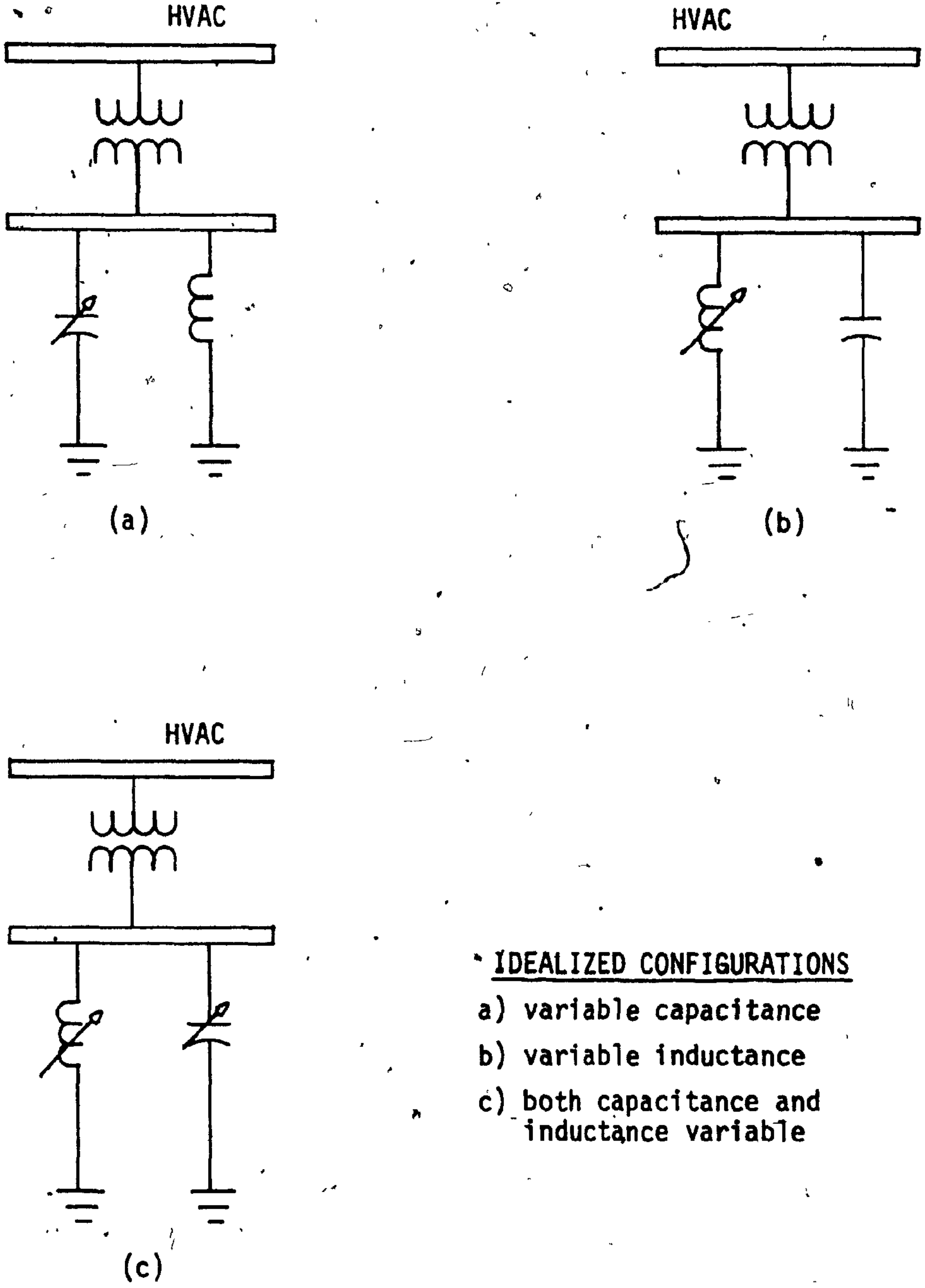
1.8 Static Var System

Since a high percentage of power system devices draw lagging current from the power systems, it may appear that the logical answer is to develop a means of controlling the var flow through the system by the amount of leading current supplied by capacitor bank near the load.

As already mentioned, a static var system consists of shunt connected, static var compensation elements with some means of controlling the var flow in and out of the HVAC network. Fig. (1.6), shows the basic configurations made up to idealize capacitive and inductive elements as they would appear at the fundamental system frequency.

Fig. (1.6a), includes a variable capacitive element in parallel with a fixed reactor, fig. (1.6b), shows a fixed capacitive element in parallel with a controllable reactor and fig. (1.6c), shows both elements as controllable. All three configurations are feasible, but (a) and (c) involve control of the capacitive leg, which in practice, is performed in discrete steps.

Static var systems take many forms, some utilizing saturable ac reactors or reactors with dc current, controlled saturation, and three basic configurations utilizing thyristors for the control of reactors or capacitive current. Only those types which utilize thyristors will be discussed in this report.



IDEALIZED CONFIGURATIONS

a) variable capacitance

b) variable inductance

c) both capacitance and inductance variable

Fig. (1.6) BASIC CONFIGURATION OF CAPACITIVE AND INDUCTIVE ELEMENTS

1.9. Types of Static Compensators

Worldwide, three basic systems have been developed, the first one using thyristors in the switching mode, the second one using phase-controlled thyristors and the third one using variable inductor. (72)

The switching mode has been used primarily with capacitors to provide varying amounts of leading vars in steps, with the size of the step determined by the needs of the application (A.S.E.A.). (118)

The phase controlled mode has been used with linear air-core reactors (C.G.E.) (82). with gapped-core reactors and with high reactance transformer to provide continously controlled inductive vars (Brown Boveri). (121)

The variable inductor has been used by two types of saturated reactors (General Electric Company, England).

1. the dc saturated reactor or transductor in which the ac output is controlled by the saturation level at which the reactor operates and,

2. the naturally saturated reactor works in the saturation region of iron.

Two thyristor equipment voltage classes are in use, low voltage in order of 1-2 kV, and medium voltage with equipments in operation at 34.5 kV or 39 kV (Laurentides, Brown Boveri).

Low voltage is an economic necessity for thyristor switching equipment because of the need for a large number of equipments in parallel. Phase controlled low voltage equipments have been used by European and Japanese manufacturers (106), in the secondaries of high reactance transformers and in some equipment designs with gapped-core reactors.

Medium voltage level -controlled designs have been used by Canadian and U.S. manufacturers operating at voltage levels ranging from 13.8 to 25 kV. These installations are all based on the principle of phase-controlled thyristors in series with linear air-core reactors.

1.10 Static Var Control and HVDC Systems

Electric power transmitted worldwide consists principally of alternating current. However, there are certain applications where direct current transmission offers distinct and/or performance advantages.

With the advent of high power thyristors in the 1960's, development of thyristor valves was initiated. Thyristor is the internationally recognized name for a particular semi-conductor device. The name is derived from the Greek, the first part meaning switch and the second part an association with the transistor family. (105)

In 1967 the General Electric Company successfully tested a prototype 200 kv, 2000 A thyristor valve. (106) Shortly thereafter, an order was placed for the world's first all solid-state system, the 320 MW Eel River Project. A number of projects are in the study or planning stage and the largest of these is the 6000 MW Ekibastus project in the U.S.S.R. (106)

S V S and HVDC systems are presently using the highest rated power thyristor available. These are 53 mm in diameter and rated 2600 V. Larger thyristors are under development and 100 mm devices rated 3800 V are already factored into new valve designs.(106)

The same basic technology that is used in static var control systems has been applied in HVDC. These systems provide a continously variable leading or lagging current.

Solid-state technology has become an important factor in the area of power transmission and utilization, namely shunt compensation for var management and system voltage control. This is referred to in general terms as static compensators, static var control or static var systems.

1.11 Thyristor Design

In order to achieve economical thyristor valves with the high ratings required for static var control and HVDC applications, individual thyristors of high voltage and current ratings are obviously desirable.

The development of thyristors has proceeded slightly differently in the different areas of the globe, conditioned by local needs. In the U.S.A., emphasis was put earlier than elsewhere on the fast type thyristor. Currently the U.S. appears to be taking the lead in the development of large-area devices, i.e., devices based on silicon wafer diameters between 65 mm and 100 mm. (116)

A Japanese speciality has been the work on very high-voltage thyristors and, initiated by the railroad industries, the development of fast high-voltage reverse conducting thyristors based on wafers of approximately 50 mm diameter. (116) European companies have invested a major effort in the development of high voltage thyristors of similar size, to be used mainly in motor controls and in high-voltage dc systems.

When we look at the thyristor we have on one end the vast range of low-cost devices, mostly in the low and medium voltage range.

Relatively recent developments in this field are the power modules and the fast turn-off (10 ms) (117) devices with repetitive blocking voltages around 500 V at elevated junction temperatures, as desired for the use in battery operated vehicles.

On the other end we have the high priced state-of-the-art devices which often find only very limited application. In fig. (1.7), we have plotted for reverse blocking and reverse conducting devices in the current range between 100A and 800A the currently available maximum forward blocking voltages versus turn-off time.

Over the last two years the limit of the repetitive peak voltage of commercially available thyristors was generally raised beyond 3 kV. A number of low voltage fast thyristors was introduced that have turn-off times as low as 10 ms. Newcomers are medium-fast high-voltage reverse blocking thyristors with typical turn-off times around 50 ms and repetitive peak voltages up to 5000 V. High-voltage reverse conducting thyristors can be even faster, since thinner silicon wafers can be employed for these. Many of the devices listed in fig. (1.7), are interdigitated structures.

This diagram gives an idea of the trade-offs one has to take today. The future might bring a shift to these curves to somewhat higher voltages as larger silicon wafers are introduced. Both curves could, in principle, shift parallel along the turn-off time axis to about half the value of the turn-off time whenever gate assisted turn-off is feasible. An extension of the curves to turn-off times beyond 800 ms appears not very likely, in view of the demands of the application engineers.

Not included in the limit curve plot of fig. (1.7), are the large and the giant phase-control high-current thyristors with diameters between 65 mm and 102 mm (130) as used in the welding and in the chemical industries. These devices with blocking voltages ranging from around 1300 V down to 600V have current ratings somewhere between 1600 A and 3000 A, respectively.

Several different types of thyristor valves have evolved over the last 10 years as indicated in Table (1.1). (117) The most widely used type is modular in construction and uses air for both cooling and insulation. Such a valve, if properly designed, provides the highest availability because of the ease of monitoring and maintenance.

In order to provide gating signals to the modules in the valves, most valve designs utilize a combination of optical and electrical signal-transmission. Interest has lately been revived in the direct light firing of thyristors. The basic light-sensitive structure is depicted in fig. (1.8). The light is radiated through the n-emitter of radius R by means of a light pipe of radius r. It is shown that for a given arrangement corresponding to a certain dv/dt capability, the high sensitivity is highest when r/R equals 1. With r typically being of the order or less than 1 mm, this calls for very small arrangements. In these, the sheet resistance of the p-base has to be high in order to keep sensitivity up in spite of the short distances to the short. Experimental thyristors of this kind had a radius R of 0.7 mm, a minimum sensitivity of approximately 10 mW (corresponding to <9 mA photocurrent) and exhibited at a temperature of 125°C a dv/dt ≈ 4000/μs up to 2000V. (131)

One such valve firing system is shown in fig. (1.9), used by C.G.E. In this system, the firing pulse generated by the static doublex control system is converted to light pulses at the valve base by means of multiplicity of light emitting diodes. The light pulses then are transmitted to the valve modules using glass light guides of special construction. At each module, the light pulse is converted back to an

PROJECT	RATING	VALVE TYPE	COMMISSIONING DATE
Eel River Canada	320 MW 2 x 80 kv, 2000 A	Air-cooled Air-insulated	1972
Tri-State U.S.A.	100 MW 50 kv, 2000 A	Air-cooled Air-insulated	1976
Skagerrak, Pole I Norway - Denmark	250 MW 250 kv, 1000 A	Air-cooled Air-insulated	1976
BC Hydro, Stage IV Canada	238 MW 140 kv, 1700 A (W)	Air-cooled Air-insulated	1977
Square Butte U.S.A.	500 MW ±250 kv, 1000 A	Air-cooled Air-insulated	1977
Shin-Shinano Japan	300 MW 2 x 125 kv, 1200 A	Air-cooled Air-insulated	1977
BC Hydro, Stage V Canada	238 MW 140 kv, 1700 A (W)	Air-cooled Air-insulated	1978
EPRI Compact Substation U.S.A.	100 MW 100 kv, 1000 A 400 kv to gnd	Freon-cooled SF_6 gas-insulated	1978
CU U.S.A.	1000 MW ±400 kv, 1250 A	Air-cooled Air-insulated	1978
Nelson River Bipole 2, Canada	900 MW ±250 kv, 1800 A	Water-cooled Air-insulated	1978
Cabora Bassa, Stage I South Africa	960 MW ±267 kv, 1800 A	Oil-cooled Oil-insulated	Delayed
Inga-Shaba, Stage I Zaire	560 MW ±250 kv, 1120 A	Air-cooled Air-insulated	Delayed

(W) Winter rating.

Table 1.1 SYSTEMS UTILIZING THYRISTOR VALVES

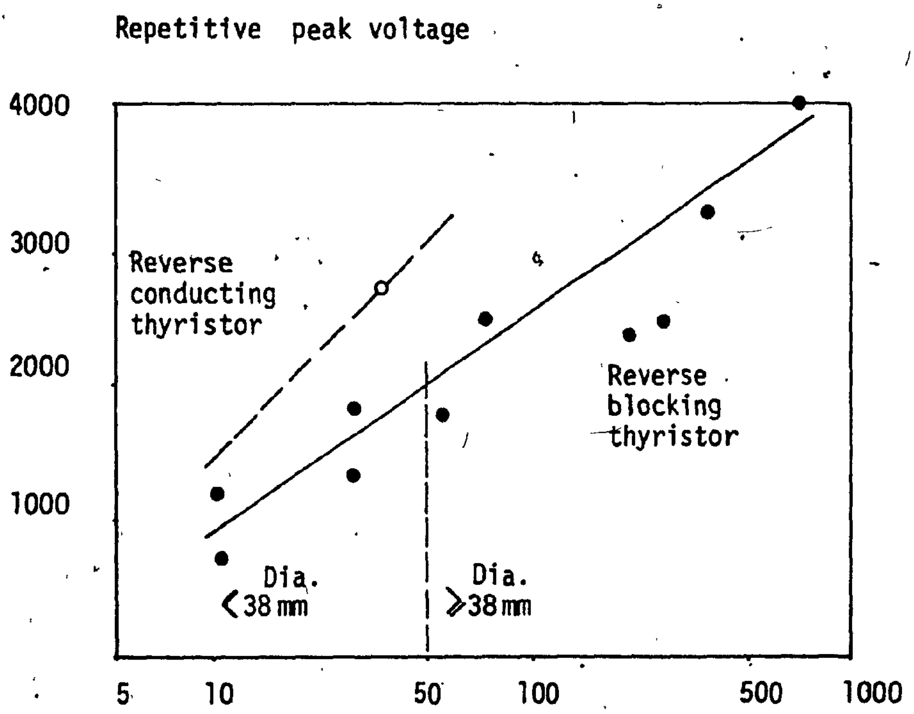


Fig. (1.7) MAXIMUM BLOCKING VOLTAGE VS. TURN-OFF TIME OF COMMERCIAL THYRISTORS

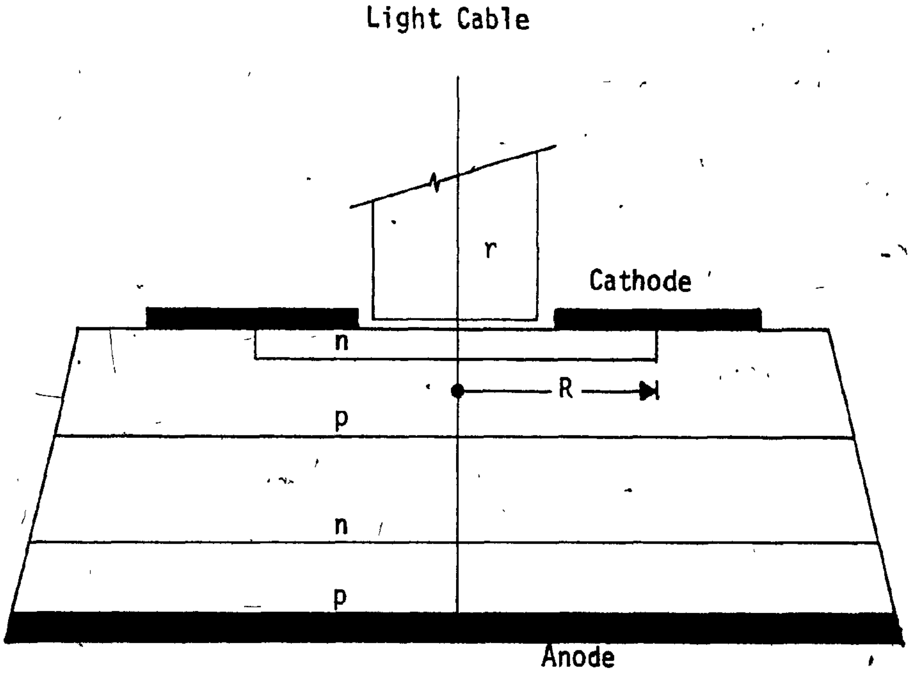


Fig. (1.8) BASIC ARRANGEMENT OF LIGHT ACTIVATED THYRISTOR

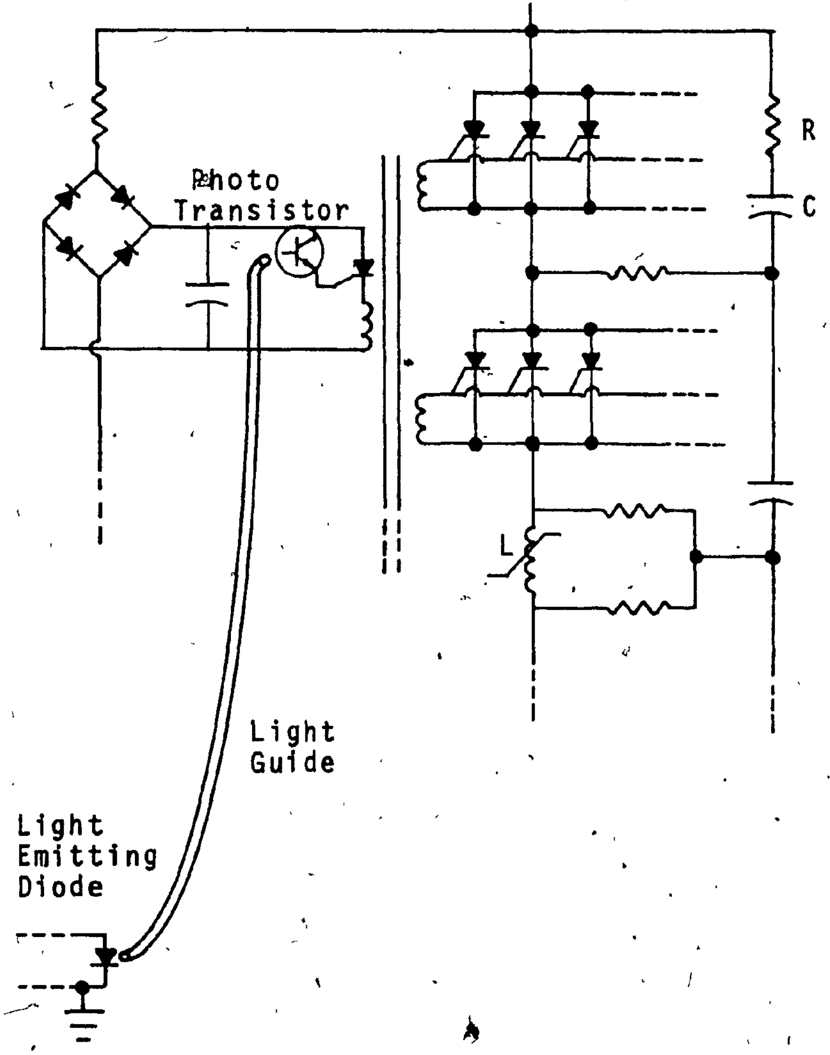


Fig. (1.9) THYRISTOR VALVE FIRING SYSTEM.

electrical pulse and distributed to all of the thyristors of the module by means of a pulse transformer. Double redundancy is utilized in the valve firing system to achieve high reliability.

The semi-conductor power devices are still in their full flow development. Blocking voltages have been reached, the UKV level of thyristors and the GKV level for rectifiers. Thyristors are manufactured with diameters 100 mm. A further increase appears possible in principle, however, the question arises where all the power to be handled by such devices is going to come from.

A progress in thyristor voltage and current ratings, as well as the anticipated future ratings are shown in Table (1.2).(106)

YEAR	CELL DIAMETER (mm)	PEAK REPETITIVE VOLTAGE RATING (volts)	AVERAGE CURRENT RATING (amperes)
1958	14	200	80
1960	24	700	150
1963	28	1300	300
1963	28	1800	225
1965	33	1800	550
1969	40	1800	750
1969	40	2600	800
1973	53	2600	1000
1975	53	2900	1000
1977	77	3800	1600
1979	77	5000	?
1982	100	5000	?

Table 1.2 PROGRESS IN THYRISTOR RATINGS

1.12 Motivation for Controlled Reactive Power Compensation

For technical and economical reasons and for the improvement of environmental conditions, it is necessary to limit all kinds of overvoltages occuring in the transmission of energy at high voltages. Especially in the case of high voltage transmission over long distances either different measures have to be taken or different possibilities discussed in order that an economical and a convenient voltage level could be obtained.

There are different methods of reactive power compensation for optimizing the performance of high voltage systems. In addition to rigid compensation using capacitors or reactors, variable reactive power supply plays a significant role.

Synchronous compensator information has not been included in this report since synchronous devices call for entirely different data format specifications already well documented.

The voltage profile of a high-voltage system i.e., maintaining the voltage at individual network modes is determined mainly by the reactive power flow in the system. Consequently, one of the major duties of the reactive compensation system is:

a) to control the reactive power flow during steady-state conditions,
b) to avoid overvoltages during faults and disturbances in the system,
c) to adjust the reactive power infeed in such a way that the transmission capability of the lines is utilized in an optimum way.

In present day power transmission systems, it is common practice for the generators to control the reactive power infeed. Non-controllable compensating equipment is used for obtaining a favourable reactive power flow:

a) shunt reactors to compensate excess capacitive reactive power of transmission lines under no load,
b) shunt capacitors for local compensation of inductive reactive power at consumer points,
c) or series capacitors to compensate the inductive reactive power due to active power transfer via lines or transformers.

When electrical energy is transmitted along lines, it is customary to operate the lines well below their surge impedance power. Maximum permissible power transmission is limited mainly by the transient transmission capability immediately following faults (stability). However, the customary shunt reactors which compensate part of the line capacitance and thus reduce the energizing overvoltages in long lines additionally increases power of transmission system. Measures which have previously been employed to increase the power transfer include:

a) increasing the number of lines
b) increasing the line voltage, and
c) in certain cases, fitting series capacitors at intermediate points along the lines.

The first two measures involve considerable expenditure and occupy extra space and the last one poses problems concerning operation and protection.

To comply with the various requirements concerning reactive power compensation in high-voltage systems and improve the degree of utilization of lines and equipment, it is necessary to employ shunt compensating equipment with the following characteristics: (71)

- reactive power variable between a capacitive and an inductive limit.
- rapid response (total reactive power boost within .1 or 2 cycles).

- no rotating mass (no inertia) and consequently no stability problems.
- no contribution to short-circuit capacity.
- minimum maintenance.
- maximum availability and reliability.
- no interference with existing protection equipment.
- no generation of ferroresonance overvoltages due to saturation.
- direct connection to transmission lines.
- no tap-changer or other mechanical control equipment.

It is obviously becoming necessary to use such compensating methods in relatively highly meshed networks alternative arrangements have been proposed recently and have already been partly put into effect in industrial power systems. All these approach, to a greater or lesser degree, the ideal characteristics described above. An international working group has made a comparison of them and compiled a table listing the main characteristics. (72)

It can be seen from Table (1.3), that only the last two methods come close to satisfying all the requirements; method h has the drawback of using a transformer which is saturated above certain voltage and the reactor transformer used in method one (i) is linear in the voltage range in question.

EQUIPMENT	APPROXIMATE RESPONSE TIME	A	B	C
a. Linear reactor		NO	NO	NO
b. Saturated reactor		NO	NO	NO
c. Static compnesator (Friedlander type)	0.02-0.05	YES	YES	NO
d. Reactor with direct current premagnetization	0.1	YES	NO	YES
e. Synchronous condenser	0.1-2.0	YES	YES	NO
f. Thyristor switched capacitors	0.01	YES	YES	YES
g. Thyristor controlled shunt reactors	0.01	YES	YES	YES
h. Thyristor controlled leakage transformers	0.01	YES	NO	YES
i. Shunt reactor transformer with controllable reactive power supply. (Static Reactor Compensator)	0.01			

A- Can frequency fluctuations be?

B. Additional tertiary winding for connection to high-voltage necessary?

C. Useable unsymmetrical compensation?

Table 1.3 SUMMARY OF CHARACTERISTICS OF REACTIVE POWER COMPENSATING EQUIPMENT

CHAPTER II

APPLICATION OF COMPENSATORS

2.1 Application of Compensators

Reactive power(var)is both generated and absorbed throughout a power system from the generators to the loads. The uncontrolled flow of reactive power can give rise to unacceptable voltages and take up rating capacity of both lines and transformers.

The control of voltage and vars on the power system - two basic functions may be performed by static var system:

- control of voltage or vars as an end in itself,
- voltage/var control as a means towards improving system stability.

The function performed by the S V S depends on the application. Specific applications are described in the following sections.

2.2 Thyristor Static Var Systems

The majority of the operating S V S installations are based on the simplified one-line diagram shown in fig. (2.1). In this approach, a thyristor controller 1 is connected in series with dry-type linear air-core reactors 2. This combination, which can be controlled to vary the current in the reactors using thyristor phase control is in parallel with fixed capacitor banks 3, which are generally supplied with filter reactors 4, to reduce system harmonic currents.(106)

The regulating system 5, responds to power system requirements, sensed by conventional current and potential transformers 6, providing gating signals at the right time in the cycle so that the S V S provides the correct amount of lagging or leading current. Since thyristor current can be changed in each half cycle, the reactive current provided by the S V S can be changed rapidly to meet power system load flow or stability requirements.

2.3 The S V S for Controlling Voltage Flicker

Probably the most challenging flicker problems to solve are caused by Arc furnace loads. The operation of Arc furnaces via a relatively low-powered network entails problems affecting

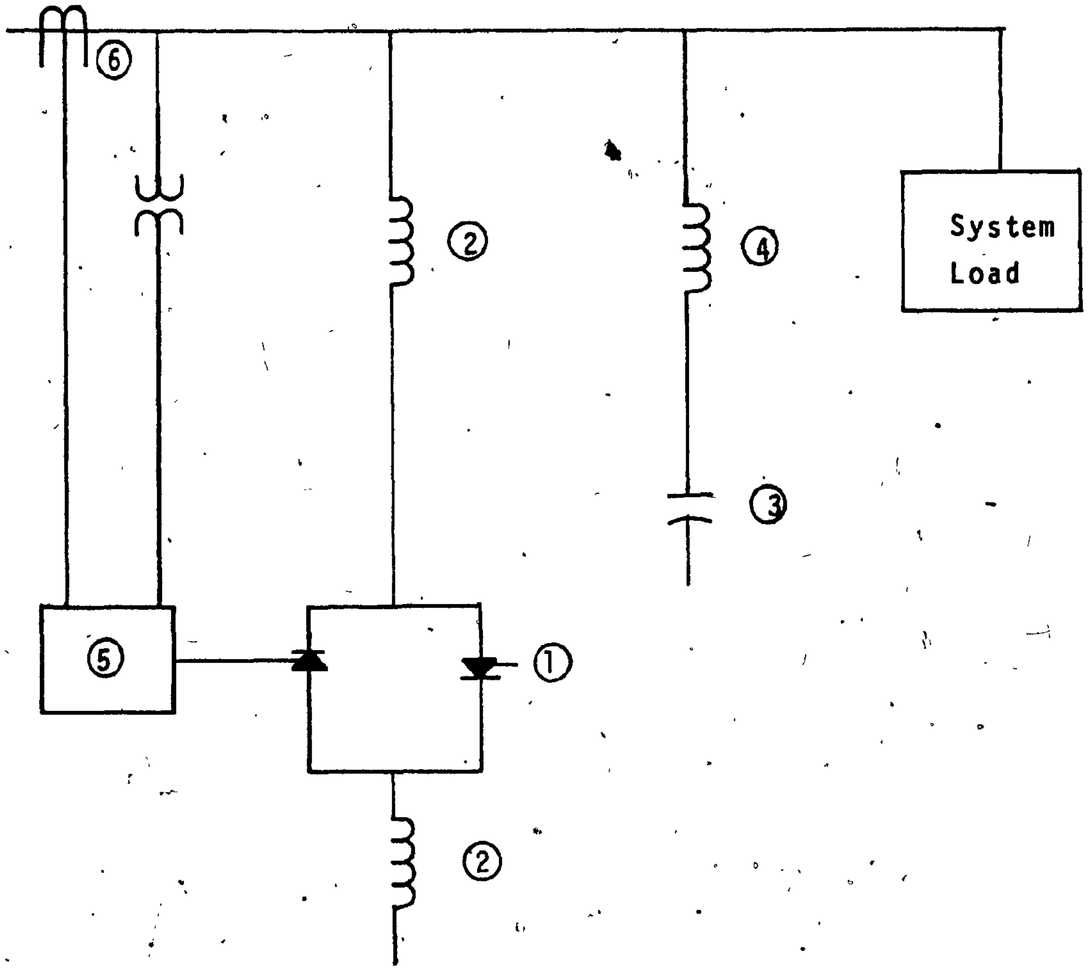


Fig. (2.1) ONE-LINE DIAGRAM OF A TYPICAL STATIC VAR CONTROL EQUIPMENT.

the transmitting capacity of the network as well as the private current consumers in an undesirable manner. The absorbtion of active and reactive power in Arc furnaces is subject to periodic and random fluctuations. Static compensation aims at reducing the resultant effect by:

- improving the power factor
- reducing voltage fluctuations (flicker)
- reducing harmonics
- balancing unsymmetrical loads

The large variation in loading to the system due to the erratic behavior of the Arc may cause "flicker" in the lights of other customers of the utility system. Utilities usually specify allowable voltage variations on a "critical bus", see fig. (1.1), Chapter 1, when connecting to the industrial customer and in some cases have even purchased the compensating equipment needed to meet these requirements. (115)

2.4 Tyristor Controller

The decision to design the thyristor controller for the 13.8 and 34.5 kV voltage classes was based on the research and development work as well as field experience in thyristor HVDC converters. The first five S V S installations provided by the General Electric Company used the same 40 mm diameter thyristor developed for the Eel River HVDC converters. The same basic thyristor cell stock was used except that the ac requirements of the thyristor controller required that two of the four thyristors be installed with reverse polarity. The ac cell stock current rating is 800 A, providing a three-phase rating in excess of 80 MVA at 34.5 kV. Currently 53 mm diameter thyristors are also used in thyristor controllers with two in parallel for 1200 A ac RMS rating, providing an equipment rating of 125 MVA at 24.5 kV. When larger ratings are needed, the thyristor controller by a single control equipment. As with HVDC converters, future single equipment ratings will be increased with the use of 100 mm diameter thyristors.(106)

Thyristors with repetitive peak blocking voltage ratings of 3000 V are in present use, with future planned voltage ratings of 3800 V. The thyristor characteristics receiving the most engineering attention are di/dt turn on, and recovery current matching due to the low load current di/dt.

Fig. (2.2), shows a typical one-line diagram of an S V S applied for Arc furnace compensation with the thyristor controller and reactors in three-phase delta configuration.

The delta circuit is used for both technical and economical reasons. Technically it makes separate phase control of each thyristor controller very simple so that the S V S can respond correctly to power system or load assymetry. This capability is especially useful in the Arc furnace application. Economically, the delta circuit reduces the current ratings of the reactors and thyristors without proportionally changing the voltage requirements.

As indicated in fig. (2.2), the thyristor-reactor equipment operates at the same voltage as the Arc furnace. This is the most economical approach for voltages up to 34.5 kV. At higher voltages, it may be more economical to use a transformer for the S V S with the voltage level and the S V S MVA rating the primary determining factors.

Fig. (2.3), shows one economical way of solving this problem using the tertiary of the Arc furnace melt-shop step-down transformer to supply the S V S. Commissioned in the summer of 1976, this installation has been described by the customer(88) as providing improved furnace operation, shorter melt cycle times and power cost saving of $50,000. per month.

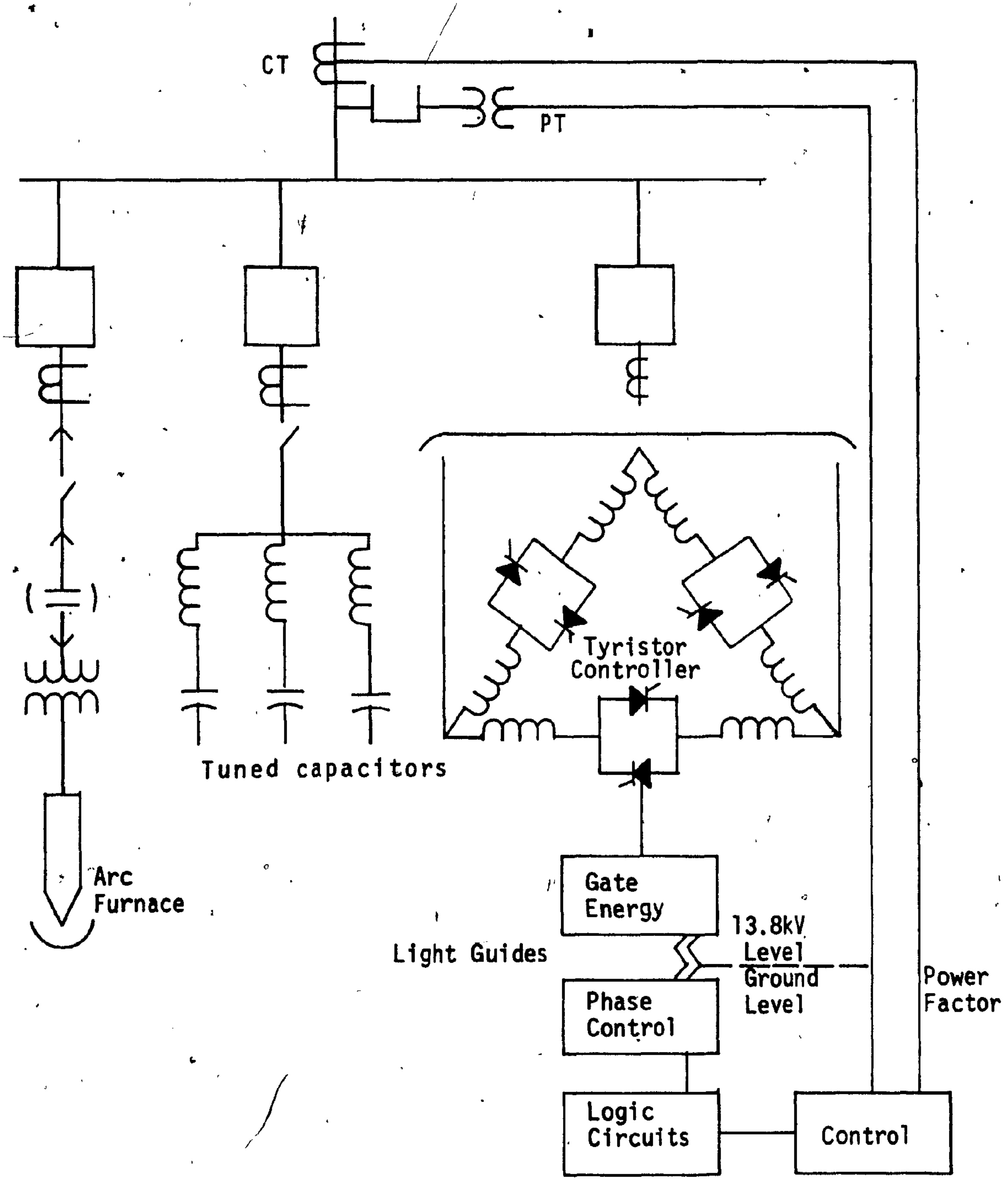


Fig. (2.2) VAR CONTROL POWER CIRCUIT AND CONTROL BLOCK DIAGRAM

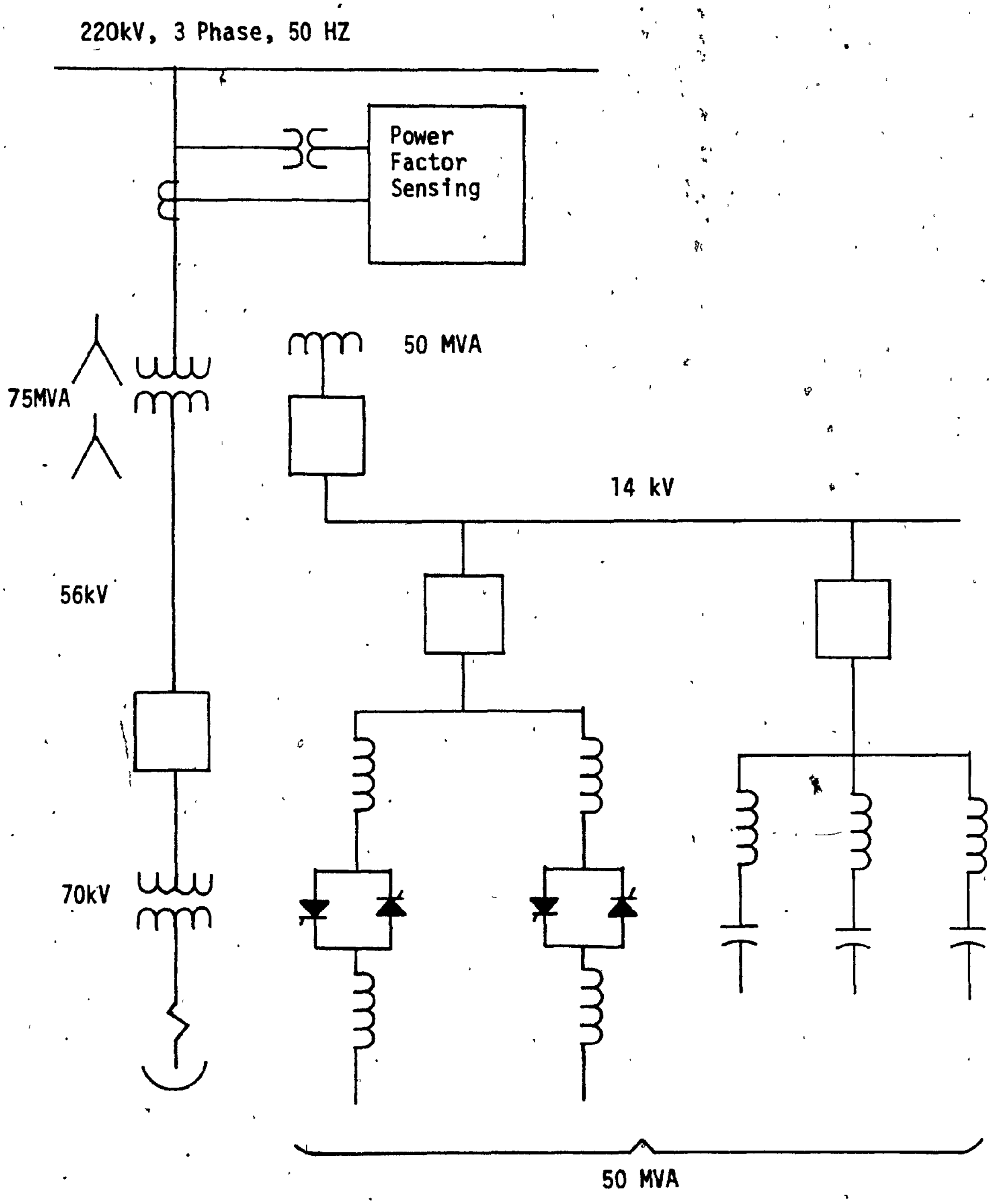


Fig. (2.3) SVS SUPPLIED FROM TRANSFORMER TERTIARY.

2.5 Control Design

The first S V S applications for compensation of Arc furnace loads required high speed of response control functions in order to operate effectively to control the voltage flicker associated with Arc furnace operation. This is done with two control modes:

a) reactive current control

and

b) current angle or power factor control

The reactive current control acts without appreciable time delay and without feed-back. The second control loop is responsive to current angle, or power factor, at the critical voltage bus. This control uses feed-back from the line current and voltage sensors and is thus a regulating control as distinguished from the open ended reactive current control. When used together the reactive current control acts rapidly as the primary control means and the power factor control serves as an adjustment to prevent drift or other error.(121)

In power system voltage control applications, the S V S output is controlled normally by a voltage regulator whose response is determined by the intereactive effects of the

S V S with other power system regulators. A high speed control function similar to the Arc furnace open loop reactive current control can be provided to bypass the voltage regulator delay in response to measured system transient conditions.

2.6 S V S Using Thyristor Controlled Reactors (TCR)

The simplest from the S V S to understand is the thyristor controlled reactor, referred to as the TCR. Fig. (2.4), shows a schematic of a typical TCR type S V S.

In the TCR, the compensation is varied by controlled voltage applied to air-core inductors by means of back-to-back connected thyristors which are phase controlled. The capacitor bank is necessary to provide the var production capability. The capacitor banks may be distributed between the high voltage and a lower voltage bus but the TCR reactor is normally operated on the lower voltage bus.

Considering the inductor/thyristor combination only, the fundamental frequency reactive current can be varied at any given system voltage by varying the firing angle of the thyristors. Fig. (2.5), shows this current as a function of conduction angle, the maximum current being drawn with full 180^0 conduction.

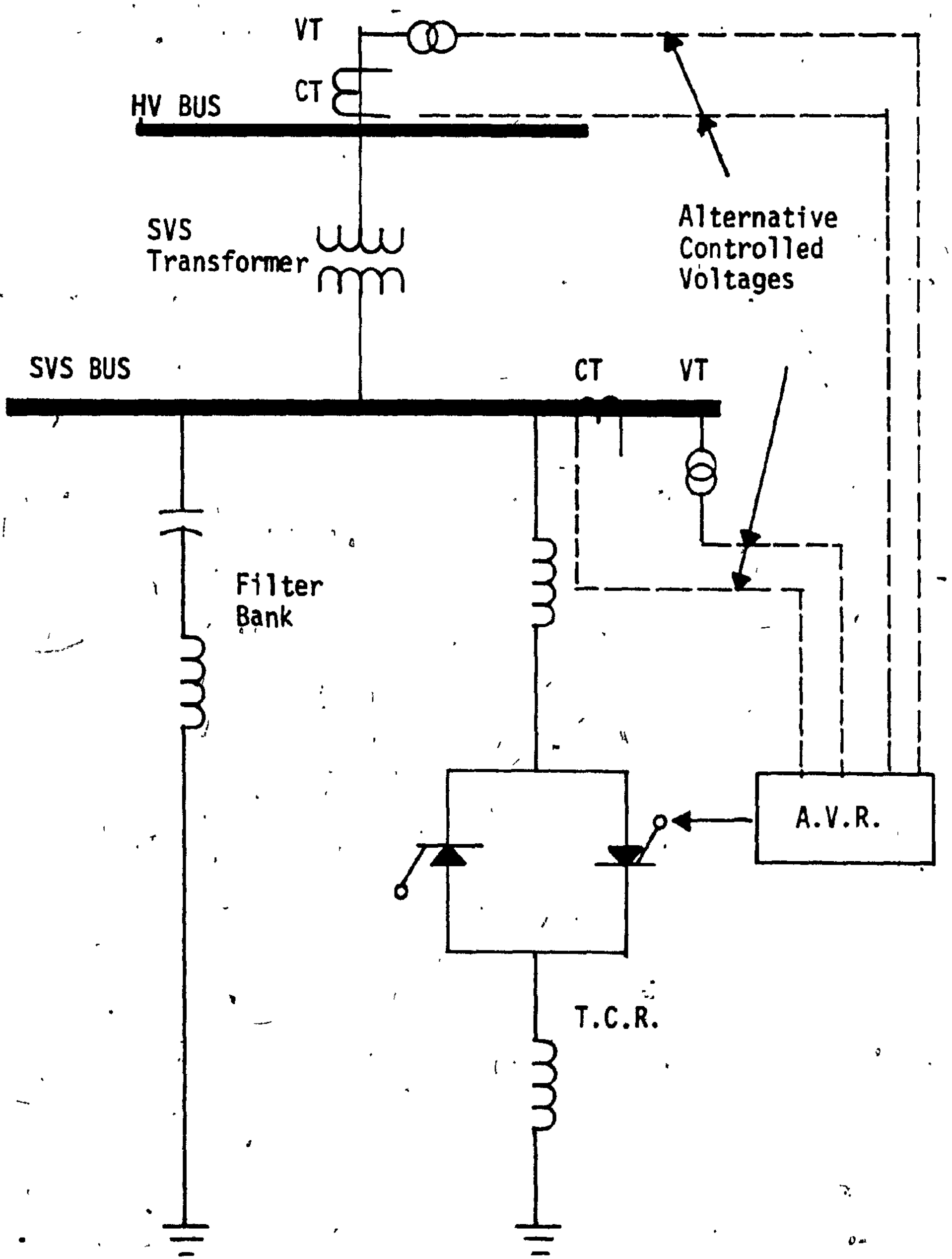


Fig. (2.4) TYPICAL SCHEMATIC OF TCR (SVS).

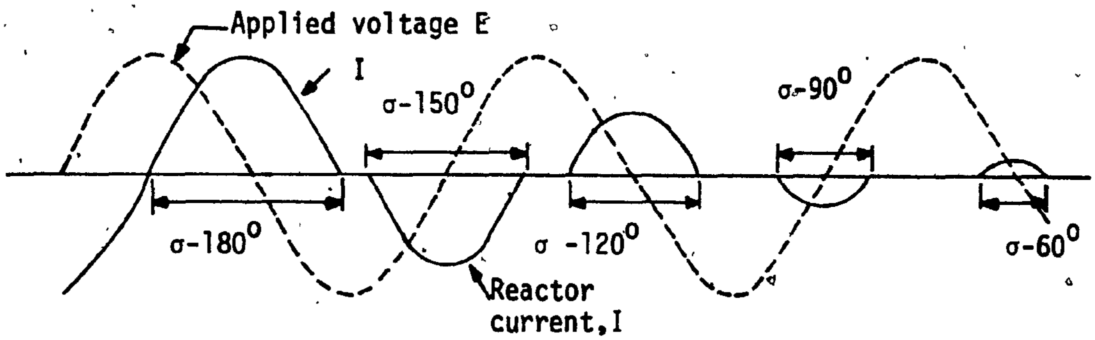


Fig. (2.5) PHASE CONTROLLED REACTOR. VOLTAGE AND CURRENT WAVEFORMS OF ONE PHASE, σ IS CONDUCTION ANGLE.

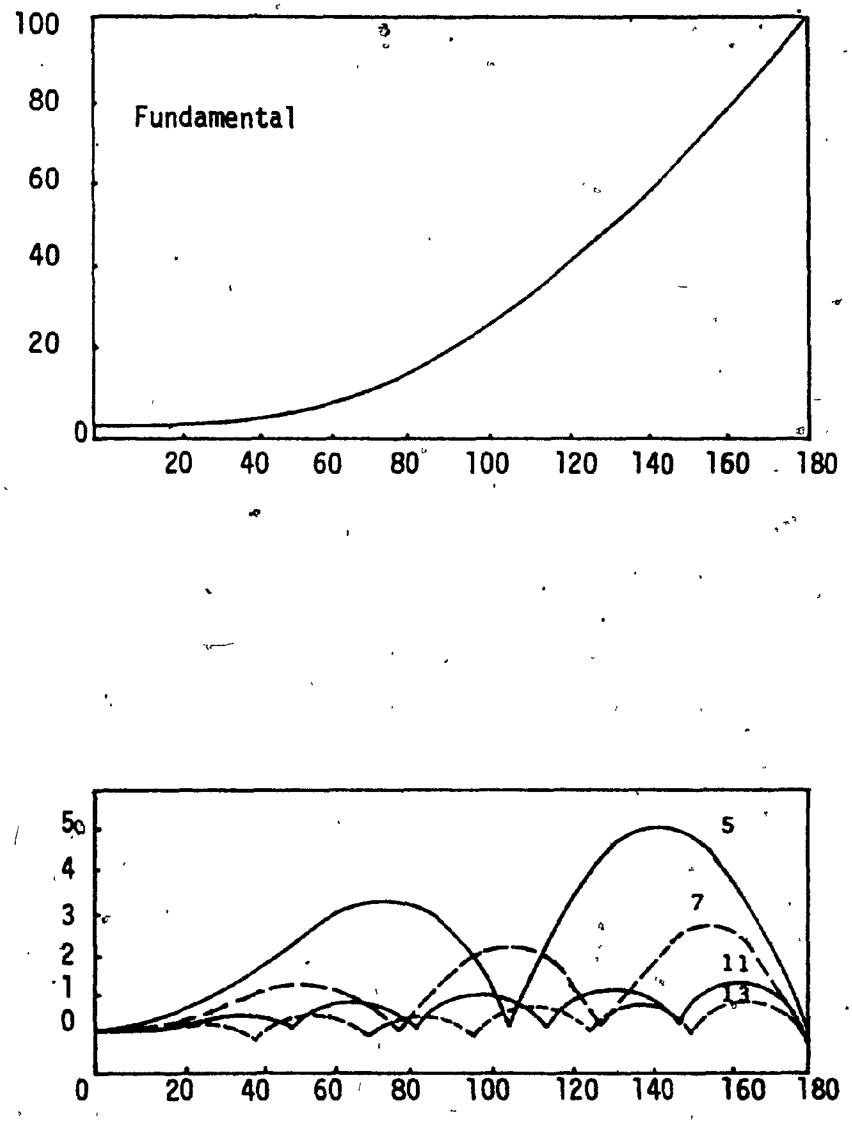
It is clear that a controlled reactive current can be obtained from the compensator which can be lagging (thyristor fully conducting) or leading (thyristor non-conducting) or anywhere in-between.(82)

2.7 Harmonic Filters

The phase control action of the thyristor controller generates harmonic currents; therefore in most cases it is desirable to provide filter banks to reduce any voltage distortion or heating these harmonic currents may cause on the power system.

If the thyristors are controlled to compensate for voltage asymmetrics during transients, third harmonic currents will also flow into the power system. It is therefore good practice to provide filtering for the fifth and seventh harmonics for balanced three-phase operation, and to include a third harmonic filter bank when asymmetrical operation of the thyristor controller is contemplated.

Fig. (2.6), shows the amount of harmonic generation as a function of the conduction angle. The harmonic content shown would not exist in practice since generally filters would be used. (82)



% of fundamental at σ-180°

Fig. (2.6) HARMONIC CURRENT GENERATED BY A 3 PHASE DELTA-CONNECTED PHASE CONTROLLED REACTOR VS. CONDUCTION ANGLE (σ) DEGREES.

By dividing the capacitor into two or three sections and placing an air-core reactor in series with each phase of each of the sections, the capacitor bank serves the dual purpose of providing the leading 60 Hz current as well as reducing the harmonic current that enters the power system.

2.8 S V S Using Thyristor Controlled Transformers (TCT)

Another form of S V S which utilizes thyristor controlled reactor current is the TCT(71, 72.) which is illustrated in fig. (2.7). It is a reactor-transformer, the secondary of which is short-circuited through thyristors. The reactance of the device can then vary from the value of magnetizing reactance when the secondary is open to the value of leakage reactance when the thyristors are gated for full wave conduction.

The primary winding is star-connected with the star point grounded. The secondary winding can be connected in the way most suitable for the valves and its voltage is made such that the valves can be operated at their full rated current.

The reactor transformer may be equipped with a delta tertiary winding for the compensation of harmonics of 3n-th order.

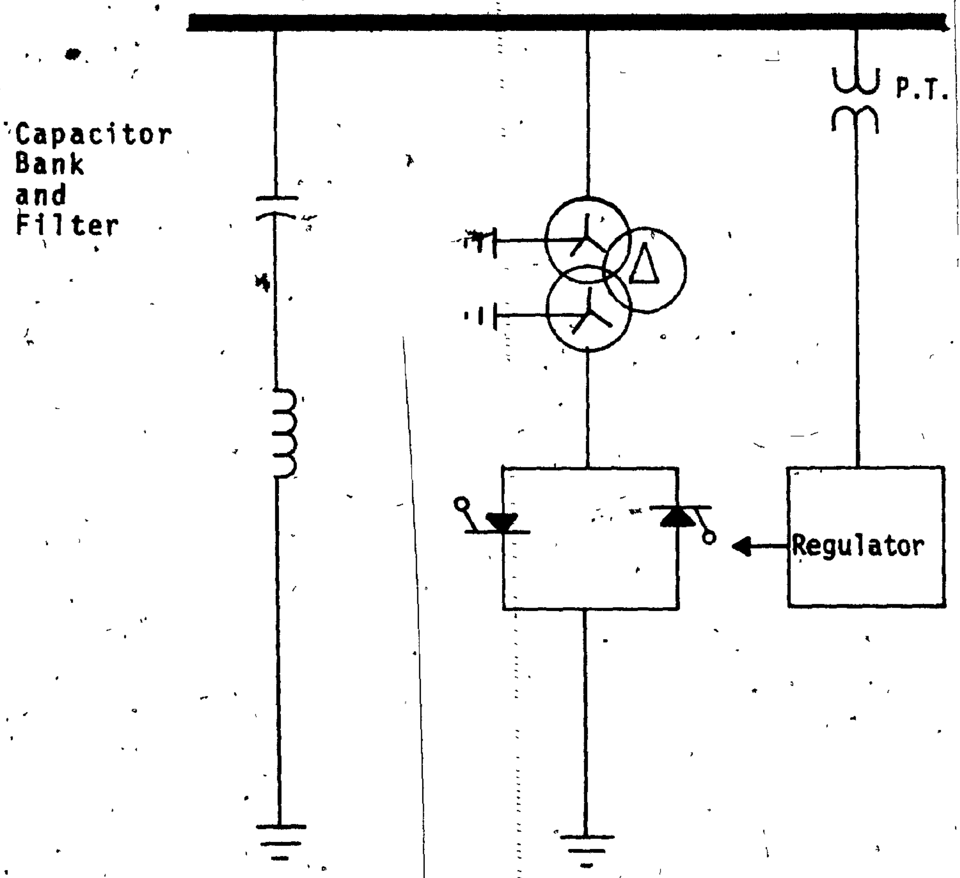


Fig. (2.7) SVS USING A REACTOR TRANSFORMER (TCT).

This tertiary winding is closely coupled to the secondary winding for good compensation.

The principal mode of operation i.e., controlling the secondary current by phase control, inherently produces harmonics in the current of the compensator under partial load conditions. Only at full load and no load are the harmonics zero. The actual harmonic content however, is dependant on the type of connection of both secondary windings and valves.

As in ac/dc converters, only certain characteristic harmonics are produced. The secondary connection which results in the lowest voltage and current design factor for the valves is the optimum one, provided the connection or means for compensating harmonics do not affect the possibility of single phase reclosure. The following secondary connections have been analysed:

1. Star connection of the secondary winding and the valves. Star points inter-connected and grounded. Additional delta tertiary winding.

2. Star connection of the secondary winding and the valves, no connection between star points.

3. Delta connection of the secondary winding as well as the valves.

In all cases the primary winding was star connected.

From table (2.1), it can be concluded that connection 1 is most suitable as regards to harmonic generation and valve rating, providing the 3n-th order harmonics are suppressed by delta connected tertiary winding, which is closely coupled to the secondary winding.

Fig. (2.8), shows the harmonics in the primary current of the reactor compensator plotted against the firing angle. It can be seen that only the fifth and seventh harmonics reach values above 1%. Even these harmonics are under 3% for a considerable part of the control range. Values between 3% and 5% arise only between 40% and 80% of the rated MVA. As the reactor compensator will operate in a system normally either below or above this range, the harmonics fed to the system should be below 3% and temporarily reach a maximum of 5%. Where the remaining harmonic content is deemed to be too high, it can be further decreased by additional filters connected to the delta tertiary winding.

CONNECTIONS	VOLTAGES RATING		MAXIMUM HARMONIC CURRENT IN %				
	Voltage X 2	Current R.M.S.	3	5	7	9	11
1	1.0	1.0	(13.7)	5.0	2.55	(1.55)	1.0
2	1.5	1.0	-	9.5	3.4	-	1.7
3	$\sqrt{3}$	$1/\sqrt{3}$	-	7.6	3.85	-	1.5

Table (2.1) COMPARISON OF THE CONNECTIONS

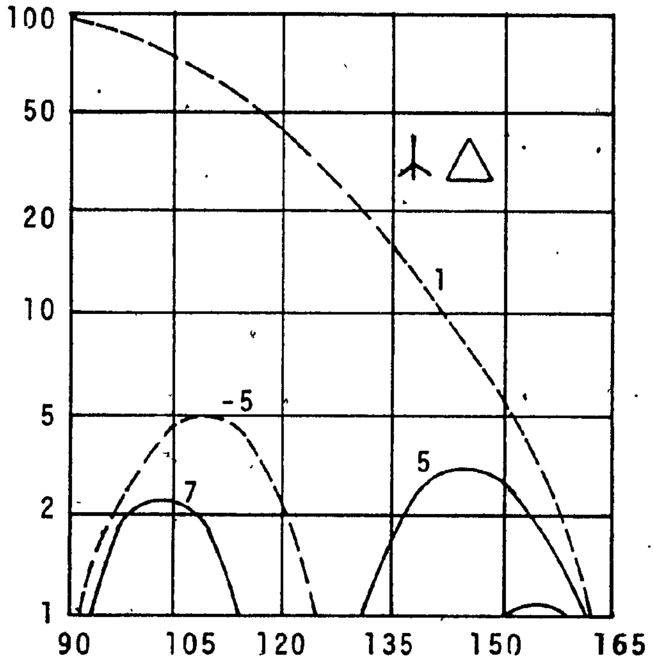


Fig. (2.8) RELATIVE HARMONIC CONTENT IN THE PRIMARY CURRENT OF THE REACTOR COMPENSATOR PLOTTED AGAINST THE FIRING ANGLE. (REFERENCE VALUE: FULL LOAD CURRENT).

Generally, in most respects the TCR and TCR Static Var Systems are functionally the same.

2.9 S V S Using Thyristor Switched Capacitors (TSC)

A third S V S which utilized thyristors is the TSC or thyristor capacitor S V C (72. 108. 118) illustrated in fig. (2.9). The basic idea of thyristor-switched shunt capacitors is to split up a capacitor bank into sufficiently small capacitor steps and switch these steps on and off individually using antiparallel-connected thyristors as switching elements. The three-phase arrangement comprises single-phase branches; with line to neutral (Y-O) or line-to-line connection. Each single-phase branch consists of two major parts, the capacitor C and the thyristor switch TY. In addition, there is a minor component, the reactor L, the purpose of which is to limit the rate of rise and the current through the thyristors and to prevent resonance with the network.

The complete TSC normally also requires a step-up transformer or tertiary winding for connection to the network.

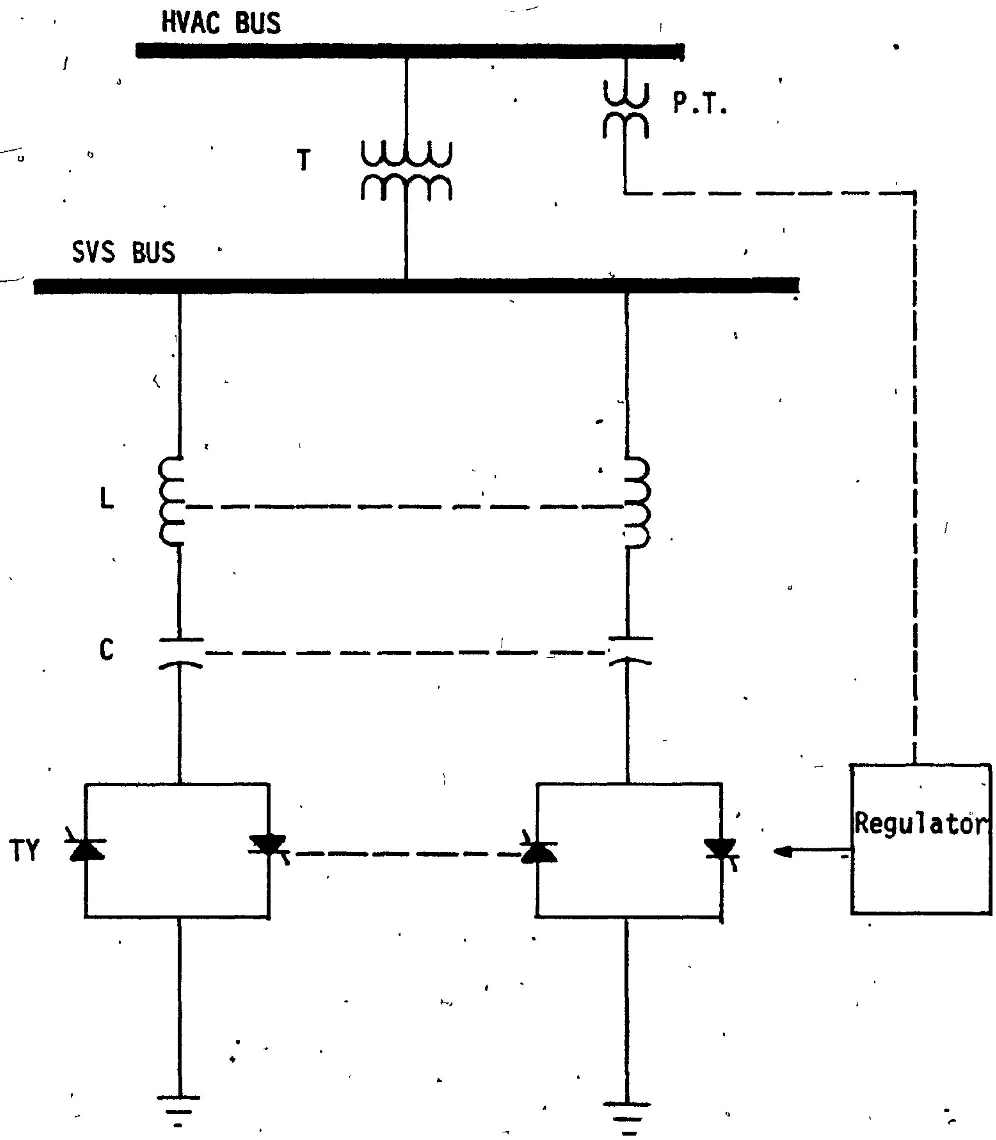


Fig. (2.9) TYPICAL SCHEMATIC OF TSC (SVS).

2.10 Switching Technique

The problem of achieving transient-free switching on of the capacitors is overcome by keeping the capacitors charged to the positive or negative peak value of the fundamental frequency network voltage at all times when they are in the standby state.

The switching on instant is then selected at the time (t_1) when the network voltage has its maximum or minimum value and the same polarity as the capacitor voltage. This ensures that the switching on takes place at the natural zero passage of the capacitor current. The switching thus takes place with practically no transients.

Switching off of a capacitor is accomplished by suppression of the firing pulses to the antiparallel thyristors so that the thyristor will block on as soon as the current becomes zero (t_2). In principle, the capacitor will then remain charged to the positive or negative peak voltage and be prepared for a new transient-free switching on. Since the capacitors, for safety reasons, are provided with discharge resistors R, a capacitor in the standby state will, however, slowly lose its voltage. To sustain the cpacitor voltage, a short firing pulse is therefore given to the last

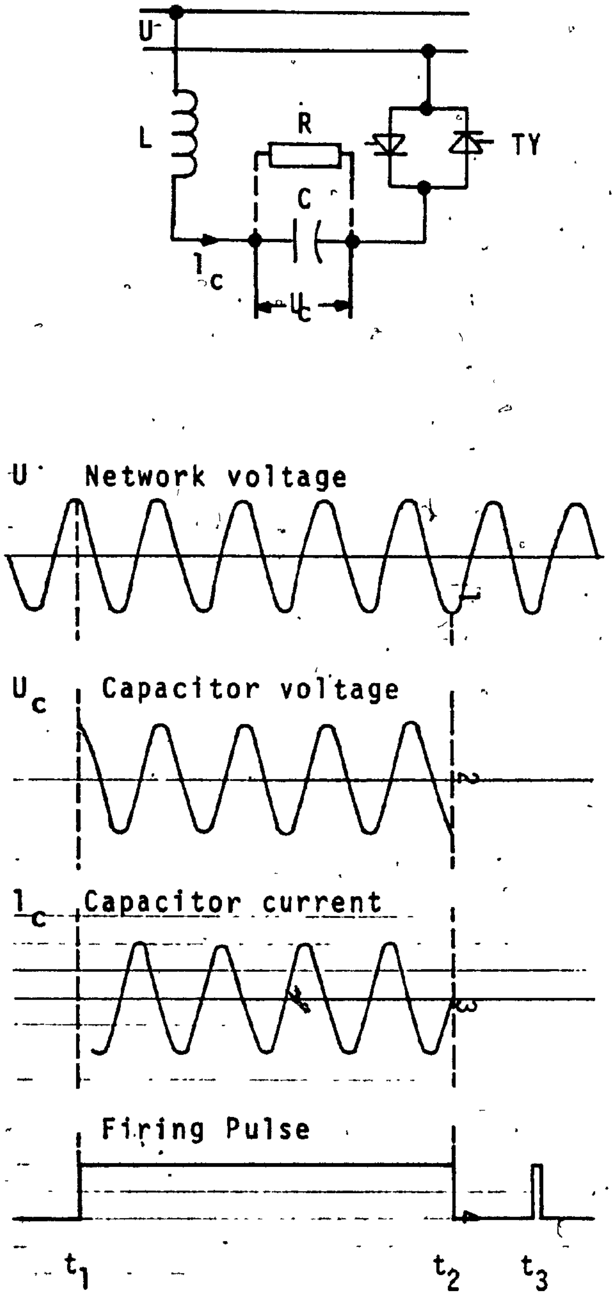


Fig. (2.10) SWITCHING PERFORMANCE.

conducting thyristor at each instant (t_3) when the network voltage is equal to the capacitor voltage, see fig. (2.10).

2.11 Harmonics

The TSC do not generate any harmonics. However, harmonics may be present in the network, which could create resonance problems because the capacitors form parallel circuits with the network impedance. To avoid such resonance problems, the branches provided with series reactors.

One advantage is enjoyed by the TSC (not shared by the TCR and TCT type S V S's) only leading vars are required for a given application; no large reactors are required. The TSC does, however, permit only discrete changes in capacitive var compared to a more continous variation in var release characteristics of the TCR and TCT types.

In comparing the TSC and TCR S V S's the functional similarity is evident. The major difference is that in the former the impedance variation takes place in discrete steps; while in the latter it is continous. Also, the TCR can generally achieve a faster dynamic response. However, the practical difference between the two schemes is considerable. The TSC scheme requires a relatively large number of small capacitor and inductor banks, each with a separate thyristor switch. The arrangement is therefore, economical only at low voltage levels. In medium to high voltage applications a step-down transformer must be used. The TCR scheme is inherently suitable for high voltage applications. Usually only the high-voltage thyristor switch is used in each phase, and depending on the total rating, the thyristor switch with the series inductor can be connected directly to the ac lines.

2.12 Voltage/Var Control on Bulk Power Networks

Another vital function static var systems can perform is to regulate voltage at strategic points on a bulk power high-voltage ac network to maintain voltage patterns in accordance with planned profiles. Profile regulation is important to insure that all transmission system loads are served with quality voltage and to avoid costly losses caused by the reactive power flows.

The Hydro-Québec Power Authority has put into service a TCR Static Var System early in 1978 in Rimouski Sub-Station, which is located in the middle of an extensive radial network of 315-230 and 161 kV lines, a long way from the main transmission system. Another reason for choosing Rimouski

Sub-Station is that the system at that point has very little voltage support. The compensator used has a capacitive rating of 85 MVAR and a 120 MVAR induction and it is used to regulate the voltage at the 230-kV level with a 3% droop. It consists of a thyristor controlled reactor, capacitor banks and a 230/24 kV transformer with ±10% taps on the high voltage side.

The largest thyristor controlled transformer (TCT) S V S envisaged to date will be in service at the end of 1978 at the higher voltage level on the 735 kV transmission system near Quebec City at Laurentides Sub-Station. That Sub-Station is relatively long way from production centers and the system should therefore benefit greatly from the additional voltage support, thus improving the stability limit of the existing 735 kV system. The nominal rating of this compensator is 330 MVAR capacitive and 100 MVAR inductive, with a 3% slope. The equipment consists of a reactor transformer and capacitors, connected directly to the 735 kV bus. The reactor-transformer comprises three-single-phase units of 150 MVA while the capacitor banks and associated filter is rated 350 MVAR at 735 kV. The thyristor valve will be connected to the secondary of the transformer at a voltage level of 32.5 kV, line-to-ground.

Another TCR-type static var system rated 10 MVAR lagging to 30 MVAR leading, commissioned (120) recently by Basin Electric Power Cooperative near Scottsbluff, Nebraska, provides tight control of steady state voltage in an area served by only two 230 kV lines with most of the generation over 300 kilometers away. Single-line outages cause undesirably large variations in the 230 kV and 11 kV system outages. Supervisory controlled capacitor banks and reactors are available, but the band width of operating voltage was reduced greatly with the S V S.

Still another TCR static var system is expected to go on line in 1978 at Minesota Power and Light Company(123). That S V S will consist of a 40 MVAR thyristor switched reactor for control of two 30 MVAR shunt capacitop banks connected on the 230 kV system. This S V S is the subject of research project RP750-1 sponsored by the Electrical Power Research Institute.

2.13 Stabilization on James Bay Transmission Systems

A few years ago, when Hydro Québec decided to develop the hydro-electric potential of the James Bay drainage area, studies were undertaken to select a system capable of transporting an estimated 16000 MW - 7700 MW from the Rupert

River, 750 Km north of Montreal and 8300 MW from La Grande River, 270 Km further north.

Various solutions were envisaged; HVDC, 1100kV , and 535 kV with either series or dynamic shunt compensation. Studies showed that the 735kV solutions offered distinct economic advantages and it was therefore decided to adopt this voltage level. Dynamic rather than series compensation seemed preferable since this form of compensation not only assures the good voltage support required by all EHV systems, but also affords greater flexibility of operation and smoother integration of future generating projects.

These system studies pin-pointed the great possibilities of increasing the stability limit of a system through the use of dynamic voltage support.(119) Computer studies have shown that the 735 kV circuits and two intermediate buses would be needed to bring the 16000 MW from the Rupert River to Montreal if no form of compensation-series of shunt dynamic were envisaged.

A further six 735kV circuits between the La Grand and Rupert complexes would complete the system. Yet this system is unable to maintain stability for a permanant line-to-ground fault in either section has less lines.

FAULTED LINES	REACTIVE POWER	
	Transient (maximum demand)	Steady-State
LG-2 Nemiskau	2200 MVAR	1170 MVAR
Nemiskau - Abitibi	2130 MVAR	1340 MVAR
Abitibi - La Verendrye	2210 MVAR	1740 MVAR
La Verendrye - Chenier	1430 MVAR	1250 MVAR

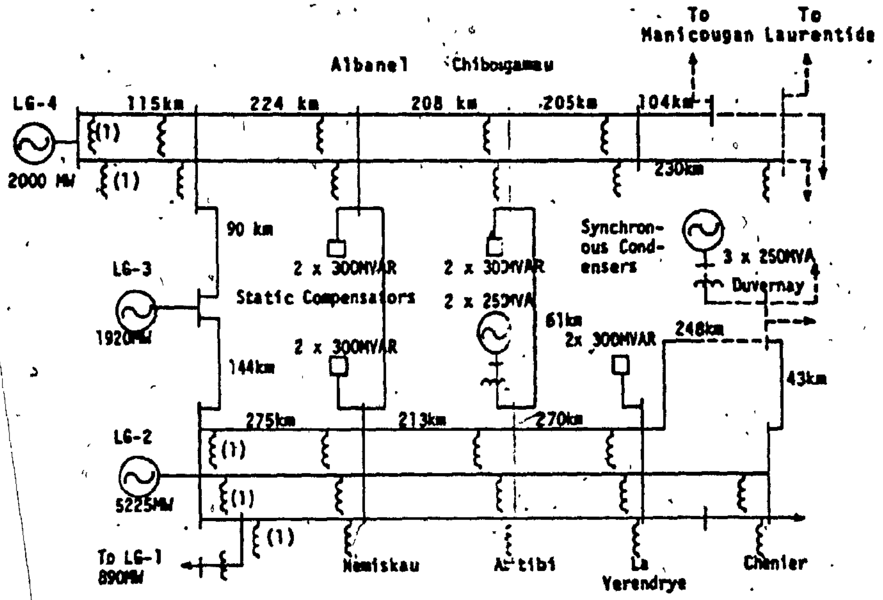
Table (2.2) REACTIVE POWER REQUIRED OF COMPENSATORS FOR DIFFERENT FAULT LOCATIONS

On the other hand, the installation of static compensators at different points along the system not only assures stability but consequently enables the number of ciruits from the Rupert River to Montreal to be reduced to six and between the La Grand and Rupert complexes, to four.

Series compensation would give the same result, if each line section were compensated 50%.(132)

A series of stability tests were conducted to attempt to determine accurately the total quantity of reactive power to be generated by the compensators installed along the network. Table (2.2), shows the quantities required on 735kV buses for faults occuring in various sections of the system; the maximum quantity needed during the first swing as well as that required in steady-state conditions. The fault condition used to determine these quantities is a permanent line-to-ground fault cleared in six cycles by the removal of the faulted line without reclosure. Fig. (2.11), shows the proposed 735 kV system.

The first two static compensators, each with a rating of 300 MVAR capacitive, are scheduled to go into service in 1981 in Nemiskau Sub-Station. These will be followed by two units at three other intermediate Sub-Stations; Albanel, Chibougamau and La Verendrye.



Note: (1) - 165 MVAR Shunt Reactors
Except as noted: 330 MVAR Shunt Reactors
-------- : existing 735 kV lines and substations.

Fig. (2.11) PROPOSED 735-kV SYSTEM FOR THE TRANSMISSION OF 10,000 MW FROM LA GRANDE.

2.14 Harmonic Measurements

The test set-up for measuring the harmonic content on ac transmission lines is shown in fig. (2.12). The circuitry of the standard TIF voltage and TIF current couplers is shown in Section 2.15 and is further described in Ref. (133) and (134).

The order of characteristic voltage harmonic found on a dc transmission line is given by kp , and the order of characteristic current harmonic found on the ac lines is given by kp±1, where k, the rectifier phase number, is the total number of rectifier conduction pulses per cycle based on the ac system frequency, and p= 1, 2, 3, ..., any positive integer. Table (2.3), gives orders of characteristic harmonics for 6 and 12 pulses converters.(135)

The line current transformer (CT) and bus potential transformer (PT) circuits utilized for the test in fig. (2.12), should, where possible, utilize non-critical circuits rather than critical metering or relay circuits, which must be removed from service during test. The secondary circuits of the CT's and PT's planned for use in making the harmonic test must be carefully analyzed to assure that any auxiliary instrument transformers or circuit loads will not distort the measured data.

The input of the noise measuring set (NMS) should be terminated in 600Ω. The NMS should be equipped with C-message weighting and flat weighting. The noise is expressed in decibel meters or decibels above reference noise in accordance with standard references for measurements on noise frequency communication circuits, that is, 0 dBRN = 24.5 x 10 rms volts across 600Ω and 0 dBRN = 90 dBM.

The spectrum analyzer (wave analyser) is used to measure the amplitude of each individual current or harmonic frequency over the band from the fundamental to 5000 Hz.

Measurements are usually taken from the output of the current and voltage transformers in a manner similar to overall noise measurements with an NMS. Depending on the type of wave analyzer used, the harmonics can be measured in terms of flat weighted (millivolts or decibels) or in C-message weighted (dBRnc) noise. The C-message weighted readings are preferred for correlation with noise data taken on voice frequency communications circuits. The flat weighted data reference to a percentage of the fundamental frequency current (or voltage) may be more meaningful to the harmonic filter system designer. Flat weighted data in dBM may be more meaningful for correlation with non-voice frequency communication circuit data.

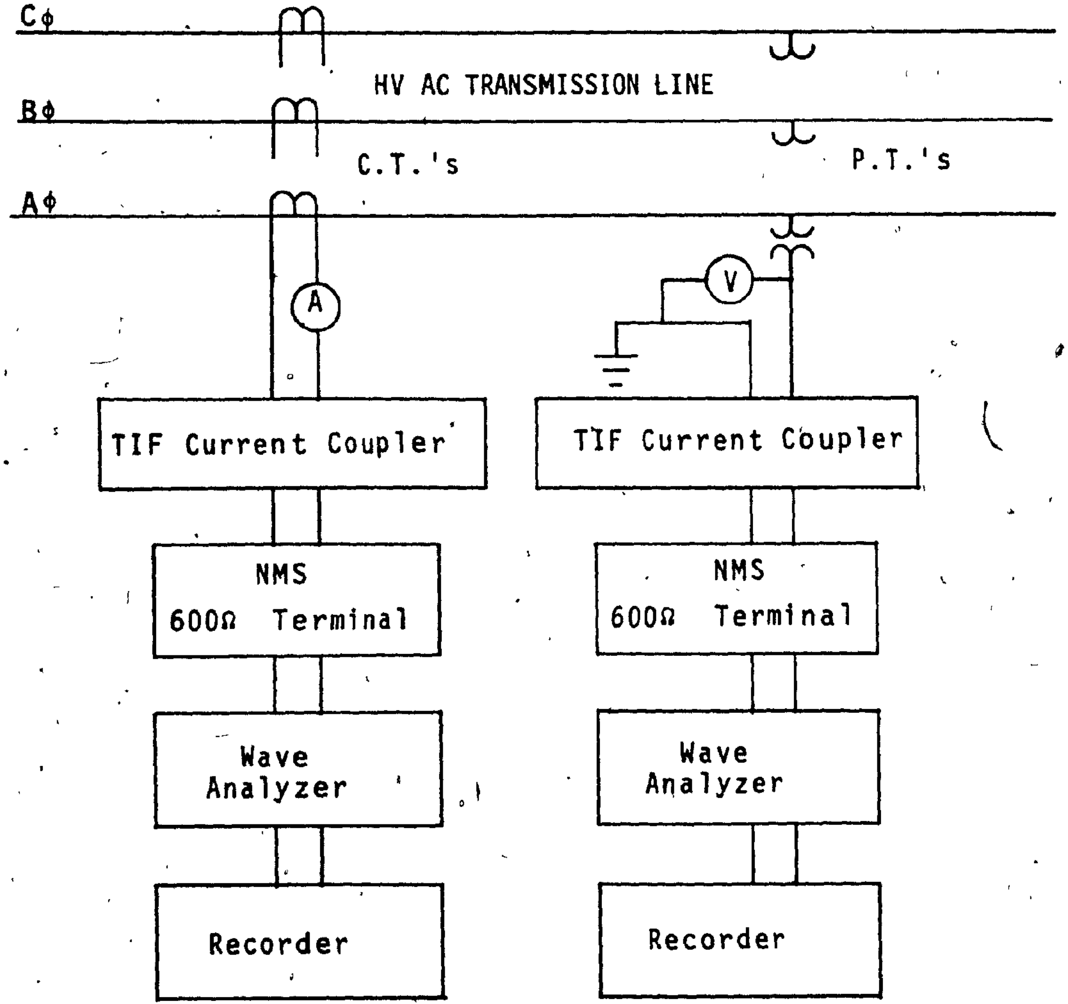


Fig. (2.12) AC POWER SYSTEM HARMONIC MEASUREMENT METHOD.

PULSE NO.	D.C. SIDE	A.C. SIDE
K	K_p	$K_p \pm 1$
6	0, 6, 12, 18, 24.	1, 5, 7, 11, 13, 17, 19, 23, 25.
12	0, 12, 24.	1, 11, 13, 23, 25.

Table (2.3) ORDERS OF CHARACTERISTIC HARMONICS.

The overall balanced (phase) I·T product on the secondary side of CT can be calculated from noise data measured in decibels above reference noise (N_1) with an NMS set that is terminated in 600Ω and used with the standard TIF current coupler. The basic equation is:

$$N_1 - 20.2 = 20 \log_{10} (I \cdot T) \tag{2.1}$$

and

$$I \cdot T_{pri} = I \cdot T_{sec} \times \text{CT ratio} \tag{2.2}$$

The overall balanced (phase) kV·T product and voltage TIF on the secondary side (phase-to-ground) of the bus or line PT's can be calculated from noise data measured in decibels above reference noise (N_1) with NMS set that is terminated in 600Ω and used with the standard TIF voltage coupler. The basic equation is:

$$N_u = 43.7 = 20 \log_{10} (kV \cdot T) \tag{2.3}$$

and

$$kV \cdot T_{pri} = kV \cdot T_{sec} \times \text{PT ratio} \quad \phi\text{-G} \tag{2.4}$$

Voltage TIF can be calculated from kV·T and the RMS magnitude of the unweighted voltage by (10) in Section 2.15

The application of frequency response correction factors to the voltage wave harmonic analysis data is desirable especially when the kV·T measurements are being used to confirm the performance specifications of harmonic filters at HVDC converter or rectifier stations. Usually the data provided by the uncalibrated PT's will enable detection of large changes in voltage TIF levels. If PT frequency response correction factors can be obtained by test and applied to the measured noise in decibels above reference noise, (3) would become:

$$(N_u \pm CF) \; -43.7 = 20 \log_{10} (kV \cdot T) \qquad (2.3)$$

where

N_u = 600Ω term. decibels above reference noise C-message wt.

CF = corrections factor normalized to the 60 Hz PT ratio in decibels above reference noise.

2.15 Telephone Influence Factor

The telephone influence factor (T.I.F.) is a dimentionless quantity which includes C-message weighting and is used to express the effect of the deviation of a voltage or current wave shape from a pure sinusoidal wave on a voice frequency communication network caused by electromagnetic or electrostatic induction, or both. The frequencies and amplitudes of harmonic present on the power circuit, among other factors, determine a power circuit's inductive influence on a voice communications circuit. T.I.F. expressed in terms of I•T product (current) and voltage T.I.F. (that is kV•T product per kilovolt) is a measure of the influence(136).

T.I.F. of a voltage or current wave is the ratio of the square root of the sum of the squares (rss) of the weighted roo-mean-squares (rms) values of all the sine-wave components (including in ac waves both fundamental and harmonics) to the root-mean-square value (unweighted) of the entire wave

C-message weighting is derived from listening tests to indicate the relative annoyance of speech impairment by an interfering signal of frequency f as heard through a modern (since 1960) telephone set. The result, called c-message weighting is shown in graphical and tabular form in 2.15 in terms of relative interfering effect P_f at frequency f.

Telephone Influence Factor

$$T = \frac{\left[\sum_{f=60\ Hz}^{f=5kHz} (A_f \cdot V_f)^2 \right]^{1/2}}{A_t}$$

where:

A_t	the total effective or rms current (I) or voltage (kv)
A_f	the single-frequency effective current (I) or voltage (kv) at frequency f, including the fundamental
W_f	the single-frequency T.I.F. weighting at frequency f.

The single-frequency 1960 T.I.F. weighting values represent the relative interfering effect of a voltage or current in an electric power circuit at frequnecy f. It is defined as:

$$T_f = W_f = 5P_f \cdot f$$

where:

5	a constant
P_f	the c-message weighting at frequency f (from table)
f	the frequency under consideration.

I·T Product

Inductive influence usually expressed in terms of the product of its unweighted rms magnitude in amperes (I) times its T.I.F., abbreviated as I·T product

$$\text{Overall } I \cdot T = \left[\sum_{f = 60\text{Hz}}^{f = 5\text{kHz}} (T_f \cdot I_f)^2 \right]^{1/2} = I \cdot (TIF)$$

where:

I_f rms current of frequency f

T_f corresponding single-frequency TIF (from table)

$T_f \cdot I_f$ singel-frequency I·T product.

kV·T Product

Inductive influence usually expressed in terms of the product of its rms magnitude in kilovolts times its T.I.F., abbreviated as kV·T product.

$$\text{Overall I}\cdot\text{T} = \left[\sum_{f\,=\,60\text{Hz}}^{f\,=\,5\text{kHz}} (T_f \cdot V_f)^2 \right]^{1/2} = \text{kV}\cdot(\text{TIF})$$

also expressed as:

$$\text{voltage T.I.F.} = \frac{\text{kV}\cdot\text{T}}{\text{kV}}$$

where:

V_f rms voltage of frequency f

T_f corresponding single-frequency TIF (from table)

kV rms magnitude of unweighted voltage

$T_f \cdot V_f$ single-frequency kV·T product

Graphs and Tables

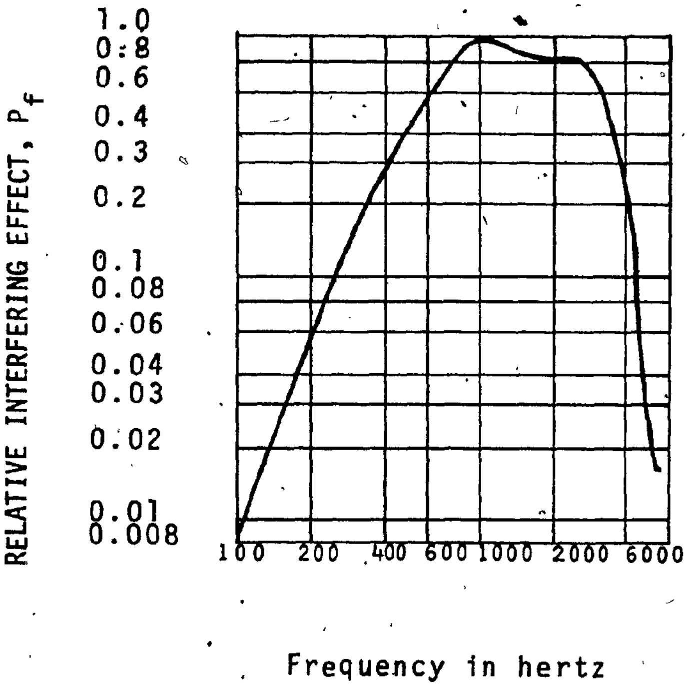


Fig. (A1) 1960 C-MESSAGE WEIGHTING CURVE

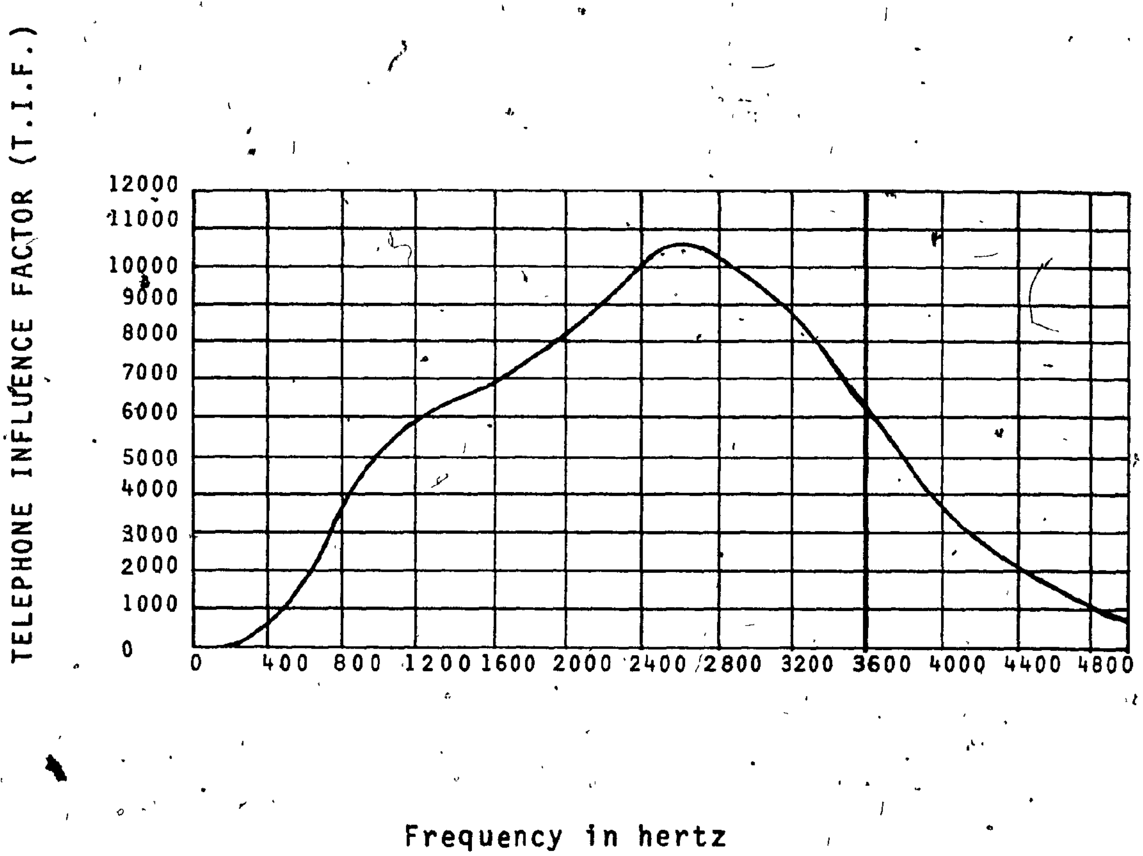


Fig. (A2) 1960 T.I.F. WEIGHTING CURVE

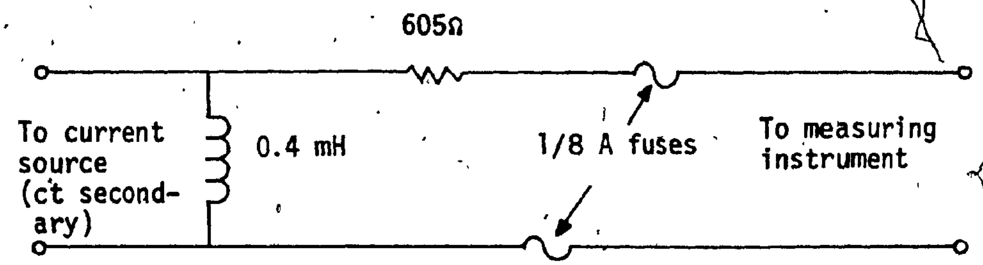


Fig. (A3) T.I.F. CURRENT COUPLER CIRCUIT

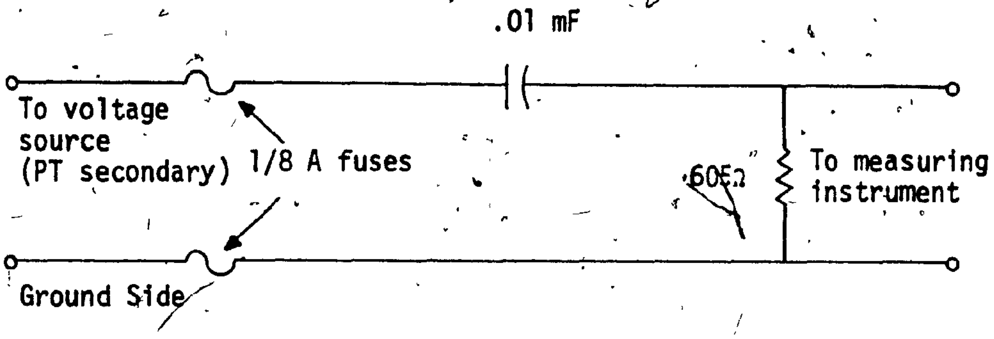


Fig. (A4) T.I.F. VOLTAGE COUPLER CIRCUIT

h	f(Hz)	C-msg	dB	TIF
1	60	0.0017	-55.7	0.5
2	120	0.0167	-35.5	10
3	180	0.0333	-29.6	30
4	240	0.0875	-21.2	105
5	300	0.1500	-16.5	225
6	360	0.222	-13.1	400
7	420	0.310	-10.2	650
8	480	0.396	- 8.0	950
9	540	0.489	- 6.2	1320
10	600	0.597	- 4.5	1790
11	660	0.685	- 3.3	2260
12	720	0.767	- 2.3	2760
13	780	0.862	- 1.3	3360
14	840	0.912	- 0.8	3830
15	900	0.967	- 0.3	4350
16	960	0.977	- 0.2	4690
17	1020	1.000	0.0	5100
18	1080	1.000	0.0	5400
19	1140	0.988	- 0.1	5630
20	1200	0.977	- 0.2	5860
21	1260	0.960	- 0.4	6050
22	1320	0.944	- 0.5	6230
23	1380	0.923	- 0.7	6370
24	1440	0.924	- 0.7	6650
25	1500	0.891	- 1.0	6680
26	1560	0.871	- 1.2	6790
27	1620	0.860	- 1.3	6970
28	1680	0.840	- 1.5	7060
29	1740	0.841	- 1.5	7320
30	1800	0.841	- 1.5	7570
31	1860	0.841	- 1.5	7820
32	1920	0.841	- 1.5	8070
33	1980	0.841	- 1.5	8330
34	2040	0.841	- 1.5	8580
35	2100	0.841	- 1.5	8830
36	2160	0.841	- 1.5	9080
37	2220	0.841	- 1.5	9330
38	2280	0.841	- 1.5	9590
39	2340	0.841	- 1.5	9840
40	2400	0.841	- 1.5	10090
41	2460	0.841	- 1.5	10340
42	2520	0.832	- 1.6	10480
43	2580	0.822	- 1.7	10600
44	2640	0.804	- 1.9	10610
45	2700	0.776	- 2.2	10480

Table (A1) C-MESSAGE WEIGHTINGS (P_f) AND 1960 SINGLE-FREQUENCY TIF VALUES. Continued....

h	f(H_z)	C-msg	dB	TIF
46	2760	0.750	- 2.5	10350
47	2820	0.724	- 2.8	10210
48	2880	0.692	- 3.2	9960
49	2940	0.668	- 3.5	9820
50	3000	0.645	- 4.0	9670
51	3060	0.603	- 4.4	9230
52	3120	0.569	- 4,9	8880
53	3180	0.550	- 5.2	8740
54	3240	0.519	- 5.7	8410
55	3300	0.490	- 6.2	8090
56	3360	0.457	- 6.8	7680
57	3420	0.437	- 7.2	7470
58	3480	0.407	- 7.8	7080
59	3540	0.380	- 8.4	6730
60	3600	0.359	- 8.9	6460
61	3660	0.335	- 9.5	6130
62	3720	0.302	-10.4	5620
63	3780	0.269	-11.4	5080
64	3840	0.240	-12.4	4610
65	3900	0.226	-12.9	4400
66	3960	0.200	-14.0	3960
67	4020	0.184	-14.7	3700
68	4080	0.168	-15.5	3430
69	4140	0.155	-16.2	3210
70	4200	0.143	-16.9	3000
71	4260	0.129	-17.8	2750
72	4320	0.112	-19.0	2420
73	4380	0.100	-20.0	2190
74	4440	0.0892	-21.0	1980
75	4500	0.0812	-21.8	1830
83.3	5000	0.0336	-29.5	840

$$T = 5_f \left(10^{(c/20)}\right)$$

$$C = 20 \log_{10} (T/5_f)$$

$$C = 20 \log_{10} (\text{C-msg } P_f)$$

NOTE: If frequency is in hertz, TIF (T) is dimensionless, and C-message weighting (C) is in decibels.

Table (A1) C-MESSAGE WEIGHTINGS (P_f) AND 1960 SINGLE-FREQUENCY TIF VALUES.

CHAPTER III

FUNDAMENTAL RELATIONSHIPS

3.1 Introduction

The three basic types of static var systems which utilize thyristors are thyristor controlled reactor (TCR), Thyristor-controlled transformer (TCT) and the thyristor-switched capacitor (TSC) types.

The fundamentals of S V S performance given in this chapter recognize the similarities between the three types. The TCR and TCT types are functionally the same and the fundamental performance characteristics are expected to be similar. The TSC involves discrete switching of capacitor banks and thereby is different from the TCR and TCT types. The performance of the TSC type S V S is assured for expediency to be similar to the other two in this chapter, where performance differences are important, they are discussed.

The basics of voltage control with an S V S are discussed first followed by examples of how that voltage control capability is used to perform vital functions on a practical HVAC power network.

3.2 First Approximation Load Flow Modeling

The simplest way to estimate the effectiveness and requirements of an S V S is to cause the load flow to hold a constant voltage ($2e = 0$), either directly on the bus of interest or behind a specified reactance. The reactance may be required either to distribute the output of several S V S in parallel, or simply to allow convergence of the solution.

Recalling the three basic configurations shown in fig. (2.4), (2.7) and (2.9), of the previous chapter the TCR and TCT types of static var systems both involve a controllable reactance. A simple constant voltage representation will show the range of reactive power required to control voltage over the operating conditions anticipated.

The constant voltage model can be refined to hold constant voltage within the control range of the device; i.e. - $B_{min} \leq B \leq B_{max}$, but outside of these limits, to fix B equal to B_{min} or B_{max}.

The relationship between the fundamental frequency component of inductive current and the applied voltage are shown in fig. (3.1a).

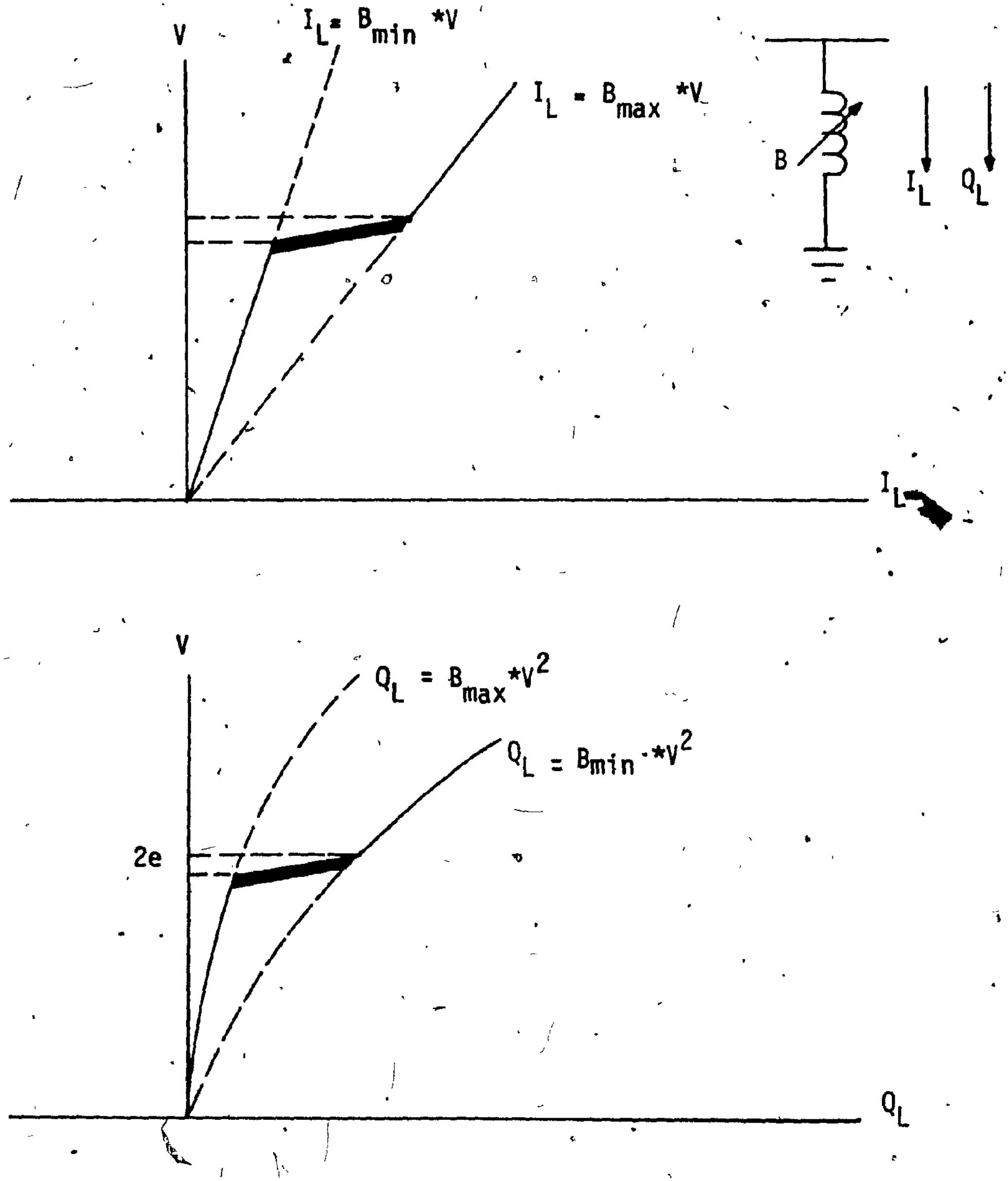


Fig. (3.1) SIMPLIFIED CHARACTERISTIC WITH SLOPE IN THE CONTROL RANGE (REACTOR ALONE).
(a) VOLTAGE -vs- CURRENT, I_L
(b) VOLTAGE -vs- REACTIVE POWER, Q_L

Alternatively, the relationship between applied voltage and reactive power consumed is shown in fig. (3.1b). The Q_L-VS-V characteristic and the I_L-VS-V characteristics both show a linear relationship within the 2e control band.

Fig. (3.2), shows a reactor paralled by a fixed capacitor with rating equal to the average reactive power consumption of the reactor and nominal voltage; i.e. $B_c = -(B_{min} + B_{max})/2$.

The use of a fixed capacitor in parallel with the controlled reactor results in the fundamental characteristic in fig.(3.2b), for $I_N = I_L + I_C$ and Q_N, respectively. The fundamental frequency characteristic in fig. (3.2a), can be obtained by graphically substracting $I_C = B_c V$ from the characteristic shown in fig. (3.1a). All harmonics are assumed to be eliminated by filters.

The relationships shown in fig. (3.2a),and (3.2b), represent the steady state behavior of both the TCR and TCT types of S V S if provided with a paralled reactor, can be characterized by the I-VS-V relationship in fig (3.2a), except the curve within the control range would be a series of discrete steps corresponding to the discrete capacitor banks switched in/out under thyristor control action.

For the remainder of the report, the discrete nature of the

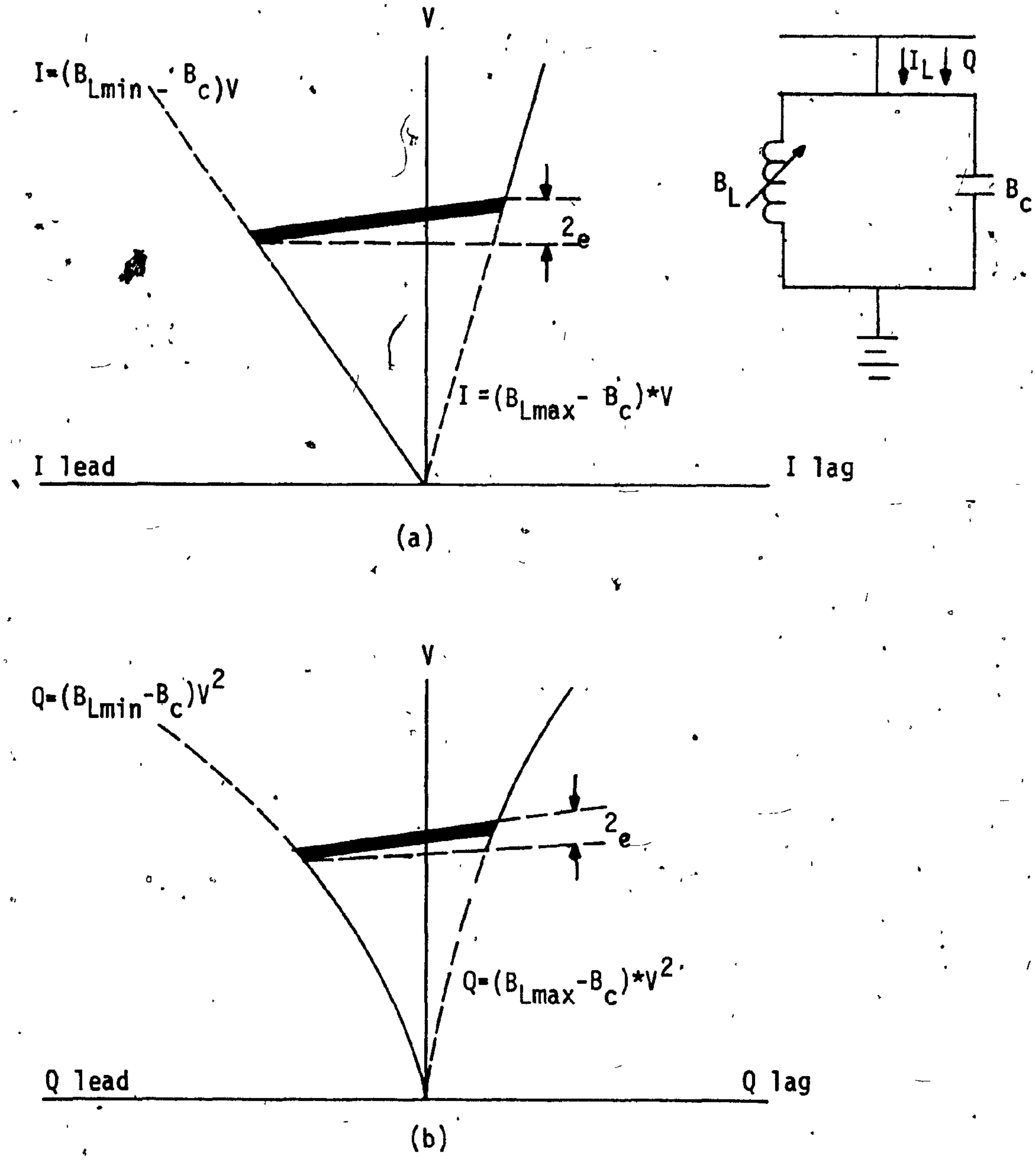


Fig. (3.2) SIMPLIFIED CHARACTERISTIC WITH SLOPE IN THE CONTROL RANGE.
(a) VOLTAGE -vs- NET SVS CURRENT, I
(b) VOLTAGE -vs- NET VARS, Q

TSC static var system will be ignored on infinite number of steps were feasible.

3.3 Voltage Regulating Performance - Fundamentals

Practical thyristor controlled var systems are generally connected to the low voltage side of a transformer when applied for voltage control of HVAC systems.

Fig. (3.3a), schematically illustrates a thyristor controlled reactor (TCR) SVS at Victory Hill (120).

The voltage on bus 2 (115 kv bus) is measured and the deviation from its desired value (error) is inputted to an automatic voltage regulator (AVR). The regulator amplifies the error and directs the thyristors to control the fundamental frequency reduce the error. The change in bus 2 voltage is a consequence of the resulting change in net reactive current (I_N in fig. (3.3a), flowing through the transformer reactance and the system impedance.

The static var system's steady state voltage control characteristics (113) shown in fig. (3.3b) depict how the regulator-controlled SVS will maintain the voltage along a nearly horizontal line passing through the set point, V_p

while operating within its rated control range. Outside of its rated control range denoted by I_C and I_L, the SVS cannot control the voltage within the desired ±.005 per unit band. For V_2 values below the control range, the SVS becomes a fixed capacitance rated for 30 MVARS at 13.8 kv and 60 hertz In like manner, for voltage values above the control range, the SVS becomes equivalent to a 10 MVAR inductor when expressed on a 13.8 kv, 60 hertz rating.

The slope of the voltage control characteristic within the control range is a function of the effective system impedance and the low frequency (dc) gain of the voltage regulator.

3.4 The Voltage Control Loop

To further understand the performance of a TCR or TCT SVS's as a system for controling HVAC voltage, the one line diagram in fig. (3.3), can be visualized in terms of the block diagram in fig. (3.4a).

Fig. (3.3) illustrates a SVS consisting of the thyristor controlled reactor (TCR) in parallel with a capacitor connected in bus 1. The diagram depicts the case where the voltage on bus 2 is being controlled by a regulator (reg) which computes a voltage error signal, amplifies that error, converts

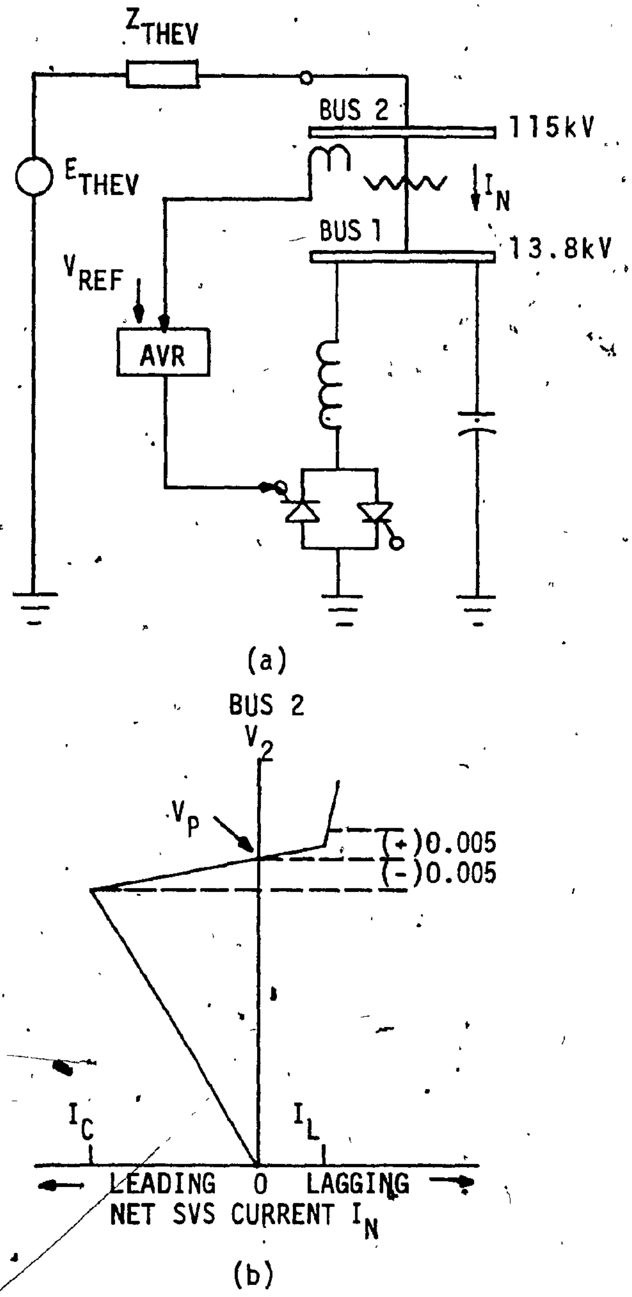


Fig. (3.3) FUNDAMENTAL REPRESENTATION OF SVS
(a) Schematic of Victory Hill SVS and System
(b) Controlled Voltage -vs- Net SVS Current; Steady State Characteristic

it to a firing angle signal and issues firing pulses to the thyristors.

Fig. (3.4), shows a functional block diagram of the voltage control loop corresponding to the SVS arrangement in fig.(3.3).

Essential elements of the static var system illustrated within the dashed box include the automatic voltage regulator (AVR), the thyristor controlled reactor (TCR), and voltage transducer. The output of the TCR block is the per unit (60 hertz) reactor admittance, B_L, which is subject to control range limits and added to the fixed 60 hertz admittance of the capacitor bank, B_C. The net admittance on bus 1 of fig. (3.3), is labeled B_1, in fig. (3.4).

The product of the net admittance B_1, and voltage V_1, yields the net current, I_N. The voltage V_2, is then visualized as the sum of I_N times a transfer impedance Z_{12} combined with contributions from other fundamental frequency current sources within the power system. Those other current sources include generators, HVDC converter stations and loads, which may all vary in response to change in V_2 as denoted by the dashed arrow.

For study of the steady state conditions of the control loop

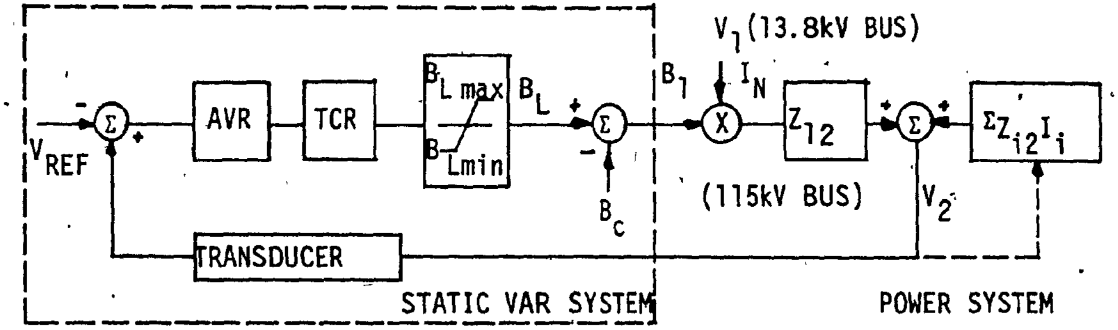


Fig. (3.4) <u>BLOCK DIAGRAM OF SVS AND SYSTEM.</u>

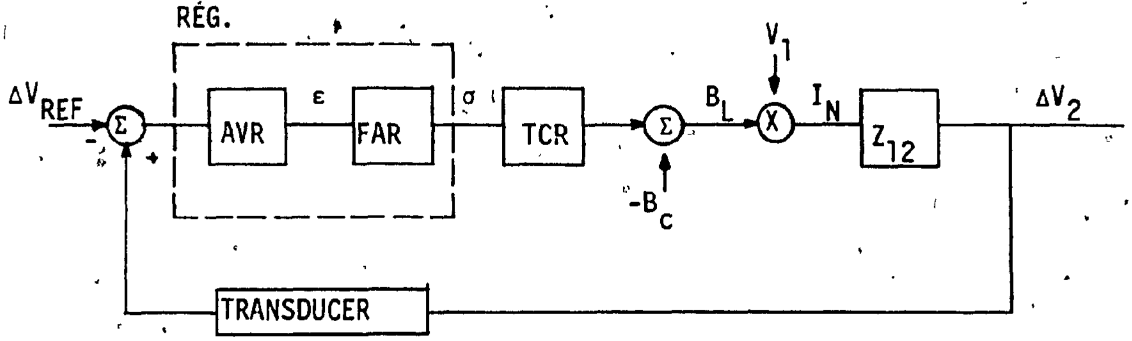
in fig. (3.4), Z_{12} and Z_{i2} are elements of the bus impedance matrix relating the bus voltages with I_N and the other steady state current injections at the active nodes. For studies of the dynamic performance of the control loop, the dynamic characteristics of the other current sources have to be considered and dynamic simulation can be accomplished using a digital computer stability program.

The block diagram in fig. (3.4), was linearized to eliminate the multiplication of B_1 and V_1 and the analysis given in Appendix A_1. The minimum value of K was 290 so a value of K=300 was adopted.

3.5 Response of Voltage Control

For an accurate assessment of the response in V_2 to SVS control action, the reaction of other voltage controllers such as those on generators, other shunt connected reactors and capacitors, and the system loads should be considered. If those factors are neglected the voltage response ΔV_2, is a function only of SVS control action.

Referring to fig. (3.5), an instantaneous change in the signal ε would be accompanied by a change in firing angle σ in the next half cycle of 50 Hz or 60 Hz supply. The admittance



where:

A.V.R.	Automatic Voltage Regulator
F.A.R.	Firing Angle Regulator
T.C.R.	Thyristor Controlled Reactor
ΔV_{REF}	Requested change in Reference Voltage
ε	Amplified Voltage Error
σ	Firing Angle of Thyristors
B_L	Admittance of Inductor
B_C	Admittance of Capacitor (filters)
V_1	Voltage on Bus 1
I_N	Reactive current in SVC transformer
Z_{12}	Power System's impedance relating ΔI_N (or ΔI_1) and ΔV_2.
ΔV_2	Resulting change in voltage on bus 2

Fig. (3.5) FUNCTIONAL BLOCK DIAGRAM OF VOLTAGE CONTROL LOOP

B_L, of the inductor, and therefore the current I_N, will settle out to a new value in about 0.5 cycle following the change in ε.

This extremely rapid response is precisely what has made the static var system so effective in minimizing voltage flicker caused by arc furnace loads. Therefore, if the A.V.R. producing the signal ε should be a pure amplifier, possessing no time constants or filtering properties, a voltage change could be completed within the transducer response plus one half cycle.

Practical transducers can be devised to cause this total response to be about one (1) cycle or less. Practical voltage regulators, however, must possess time constants to prevent amplifying the ever-present noise in the sensed HVAC voltage. The flicker control SVS applications utilize controls which regulate voltage indirectly by negating the reactive current surges causing the flicker. The reactive compensation scheme is useful when the load causing the voltage variation is fed radially, but cannot be used effectively for direct control of the voltage on a bus in an HVAC network.

Consequently, for continuous control of the normal, relatively small variations in voltage, the SVS response to a change in V_2(or V_{ref}) is reduced slightly by the presence of necessary filtering effects in the A.V.R. The settling time for a change in ΔV_2 will therefore be about 1.5 to -2 cycles on a power system where rapid SVS control actions are not met with equally fast counteractions.

3.6 Control Approaches

The compensating current can be adjusted with a practical "variable susceptance" only at discrete instants of time, once in each half cycle of the applied voltage. The means of control is a solid state (thyristor) switch that can be turned on ("fired") at will, but it can only be turned off when the current reaches zero (natural commutation). However, to ensure transient-free switching, the firing of the thyristor switch must be synchronized to the ac system voltage. Using the switched capacitor/inductor scheme, the firing of the thyristor switch must coincide with the peaks of the ac voltage. In the thyristor-controlled inductor scheme the conduction of the thyristor switch can be initiated anywhere in the "firing interval" stretching over 90 degrees from the peak to the subsequent zero crossing of the applied voltage. The final information in the switched capacitor/inductor scheme is the number of capacitor (or inductor) banks to be connected to the ac line, and that in the thyristor controlled inductor scheme is the delay angle at which the firing of the thyristor switch is to be initiated. In both cases the operation of the control must be rigidly synchronized to the ac system voltages.

Three basic control approaches are generally employed:

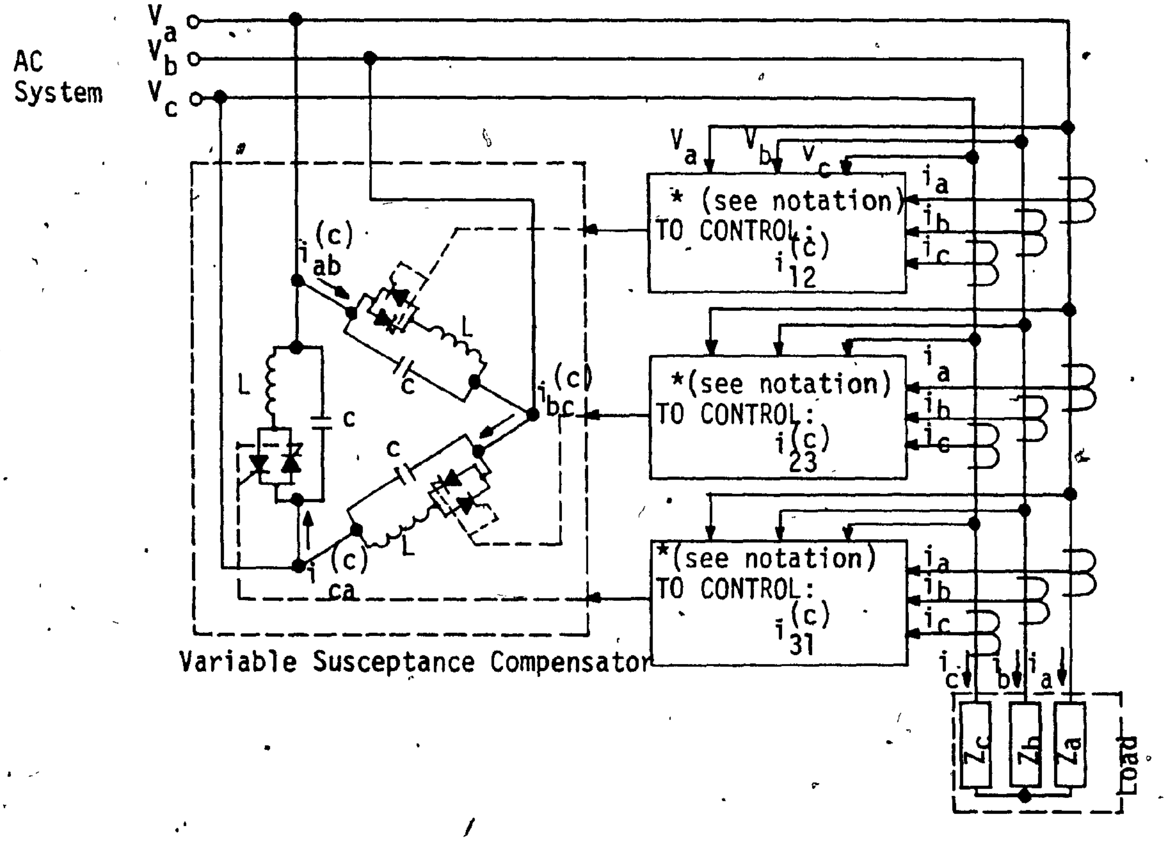
1. The first is a directly computational, so called "feed forward" method, which repeatedly solves a set of appropriate steady state equations to find the susceptances (or currents) required for compensation.

2. The second is a feedback control, in which the compensating susceptances are closed-loop controlled so as to reduce certain error signals.

3. The third approach may be termed hybrid; it uses a combination of the feedforward and feedback control techniques.

The first approach is normally suitable only to control load compensators. The second one is usually used to control compensators regulating, terminal voltage. The third approach may be used to control either type of compensator. These basic control approaches are discussed below in connection with the compensator which uses the thyristor-controlled inductor. They are of course, equally applicable to a switched capacitor/inductor type compensator.

All feedforward (computational type) control approaches are based on the fundamental presumption that the load (and the ac system) is in "steady state" between any two consecutive instants of time at which the current in the compensating susceptance is changed. Thus, between these time instants the relevant load currents (or powers or impedances) can be measured and from these, the required compensating current can be determined (computed) using appropriate steady state equations. Since the operation of each thyristor-controlled inductor (representing, with the corresponding fixed capacitor, one of the three variable susceptances) is synchronized to the line-to-line voltage to which it is connected, it follows that the processing of each of the three steady-state equations expressing the required compensating current (susceptance) in terms of the quantities characterizing the load (current, powers, or impedances) is carried out over time intervals which are mutually displaced by a third of the period time of the ac system voltage. The three compensating currents are essentially controlled independently of each other as shown schematically in fig. (3.6).



*Notation - Measuring, Computing and Signal Processing Circuits.

Fig. (3.6) A GENERAL LOAD COMPENSATION SCHEME USING FEED FORWARD (COMPUTATIONAL) TYPE CONTROL.

The three load current components can be expressed as follows, by converting the phaser quantities into appropriate time functions.

$$\begin{aligned}
B_{ab}^{(c)}(\sqrt{3}\,V) &= -K_1\, i_b(t))\Bigg|_{\substack{V_{bc}>0 \\ dV_{bc}/dt\,=\,0}} -K_2\, i_a(t)\Bigg|_{\substack{V_{ca}>0 \\ dV_{ca}/dt\,=\,0}} \\
B_{bc}^{(c)}(\sqrt{3}\,V) &= -K_1 i_c(t))\Bigg|_{\substack{V_{ca}>0 \\ dV_{ca}/dt\,=\,0}} -K_2 i_b(t)\Bigg|_{\substack{V_{ab}>0 \\ dV_{ab}/dt\,=\,0}} \\
B_{ca}^{(c)}(\sqrt{3}\,V) &= -K_1 i_a(t))\Bigg|_{\substack{V_{ab}>0 \\ dV_{ab}/dt\,=\,0}} -K_2 i_c(t)\Bigg|_{\substack{V_{bc}>0 \\ dVbc/dt\,=\,0}}
\end{aligned}\tag{3.1}$$

The expression, for example, $i_b(t)\Bigg|_{\substack{V_{bc}>0 \\ dV_{bc}/dt\,=\,0}}$

Simply means to take the value of current $i_b(t)$ at the instant of time when the derivative of $V_{bc}(t)$ is zero and $V_{bc}(t)$ is positive, or in practical terms, to sample the current $i_b(t)$ at the positive peak of voltage $V_{bc}(t)$.

Evidently the quantity so obtained is the amplitude of the component of current $i_b(t)$ that is in phase with voltage $V_{bc}(t)$.

Consider as an example the use of eq. (3.1) for control of the compensating current, i_{ab}, in phase ab. The relationship between the amplitude of the compensating current,

$$I_{ab}^{(c)} = \sqrt{3} \quad V \ B_{ab}^{(c)} \tag{3.2}$$

is {first line of eq. (3.1)}.

$$I_{ab}^{(c)} = -K_1 i_b(t) \left| \begin{matrix} V_{bc} > 0 \\ \\ dV_{bc}/dt = 0 \end{matrix} \right. -K_2 i_a(t) \left| \begin{matrix} V_{ca} > 0 \\ \\ dV_{ca}/dt = 0 \end{matrix} \right. \tag{3.3}$$

which, for simplicity, may be written in the form;

$$I_{ab}^{(c)} = -K_1 I_{b,bc} - K_2 I_{a,ca} \tag{3.4}$$

where $I_{b,bc}$ means the value of $i_b(t)$ at the time when $dV_{bc}/dt = 0$ (and $V_{bc}) > 0$), and $I_{a,ca}$ means the value of $i_a(t)$ when $dV_{ca}/dt = 0$ (and $V_{ca} > 0$).

The net compensating current provided by the fixed-capacitor and the thyristor-controlled inductor is expressed as a function of delay (firing) angle α:

$$I_F(\alpha) = I_c - I_{LF}(\alpha) = V\left(wC - \frac{1}{wL}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)\right) \qquad (3.5)$$

If (α) is positive when the total current is capacitive $(I_c > I_{LF}(\alpha))$ and negative when the total current is inductive $(I_{LF}(\alpha) > I_c)$.

This in the present case is:

$$I_{ab}(\alpha_{ab}) = I_{c,ab} - I_{LF,ab}(\alpha_{ab}) \qquad (3.6)$$

Where $I_{c,ab}$ is the current in the fixed capacitor, and $I_{LF,ab}(\alpha_{ab})$ is the fundamental current in the thyristor-controlled inductor.

In order to provide the current $I_{ab}^{(c)}$, the delay angle α_{ab} has to be set so as to satisfy the equality:

$$I_{ab}^{(c)} = I_{ab}(\alpha_{ab}) \qquad (3.7)$$

or, with substitution of eqs. (3.4) and (3.6).

$$I_{LF,ab}(\alpha_{ab}) = I_{c,ab} + K\ I_{b,bc} + K_2\ I_{a,ca} \qquad (3.8)$$

Thus in eq. (3.8) the current of the thyristor-controlled inductor is defined in terms of the fixed-capacitor current and components of the load current flowing in phase a and b. The remaining problem is simply to find angle α_{ab} that corresponds to the required inductor current $I_{LF,ab1}$. In other words, the following equation:

$$\frac{\sqrt{3}\;V}{wL}\left(1-\frac{2}{\pi}\alpha_{ab}-\frac{1}{\pi}\sin 2\alpha_{ab}\right)=I_{c,ab}+K_1 I_{b,bc}+K_2 I_{a,ca} \qquad (3.9)$$

where

$$I_{LF}=\frac{V}{wL}\left(1-\frac{2}{\pi}\alpha-\frac{1}{\pi}\sin 2\alpha\right)$$

$$0 \leq \alpha \leq \frac{\pi}{2}$$

has to be solved for α_{ab} to know at what time instant the thyristor switch is to be fired. The above procedure indicates that the feedforward control scheme requires two main functional elements as illustrated by the block diagram of fig. (3.7), one to compute the desired inductor current, the other to convert the desired inductor current to a corresponding firing angle.

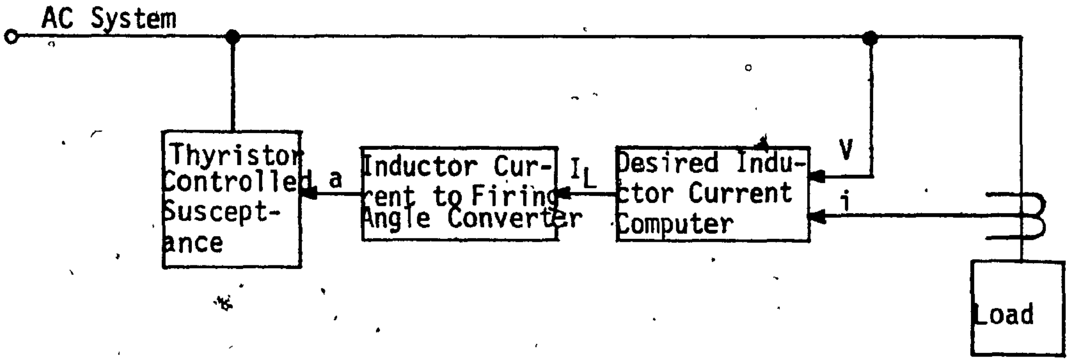


Fig. (3.7) MAJOR FUNCTIONAL ELEMENTS IN A GENERAL FEED FORWARD CONTROL SCHEME.

The possibility of using a feedback control approach for regulating the terminal voltage of an ac transmission network by a shunt compensator has already been briefly discussed.

Similar "closed loop" approaches can, of course, also be used to accomplish the objectives of load compensation (balancing and power factor correction).

In principal all feedback controls work similarly. The thyristor-controlled inductor (providing with the fixed capacitor the variable susceptance) is made to respond to an appropriate error signal. The error signal represents the difference between a chosen reference and a corresponding parametric value of the variable to be controlled. Any change in the error signal results in an opposing change in the effective susceptance value of the thyristor-controlled inductor. This tends to keep the error constant and close to zero. The block diagram of a typical feedback control scheme is shown in fig. (3.8).

There are three basic functional elements in the control loop: the error generator, error processor, and error to firing angle converter. The input signals to the control are the line currents and/or voltages of the ac system.

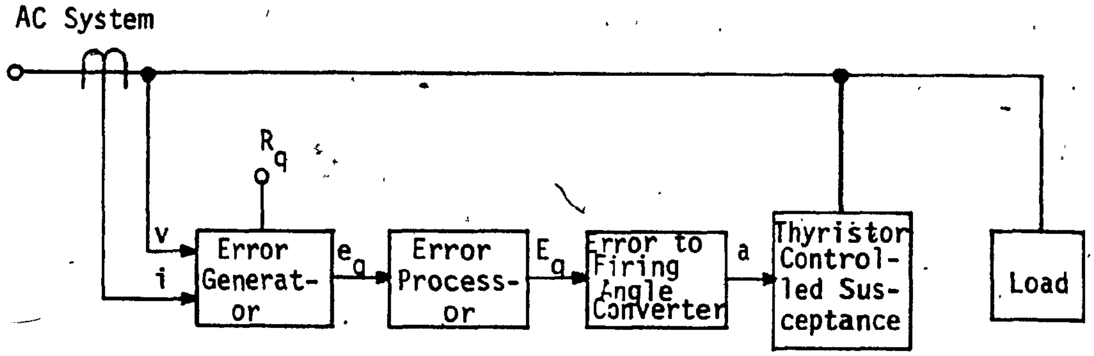


Fig. (3.8) MAJOR FUNCTIONAL-ELEMENTS IN A GENERAL FEEDBACK CONTROL SCHEME.

The function of the error generator is, first, to derive a parametric value of the variable q to be controlled (e.g.; the positive sequence and negative sequence current or voltage components, reactive line current components, reactive power, etc...) and, second, to generate an error signal, e.g.; by comparing the parametric value of the variable derived with the reference signal Rq. The error processor provides an output signal, Eq, which is generally a sum of two terms. The first is proportional to the error signal, e_q, and the second is proportional to the integral of eq.

The error to firing angle converter converts the processed error signal, e_q, to the firing angle to the thyristor switch. The firing angle generation must, of course, be synchronized to the appropriate line-to-line voltage and repeated in every half cycle.

The feedforward and feedback control approaches are complementary. The feedforward control is inherently stable and can be made fast. The feedback control is inherently tolerant to changes in the control elements as well as the controlled system and can be made very accurate. For these reasons, they are frequently used together in practical control schemes.

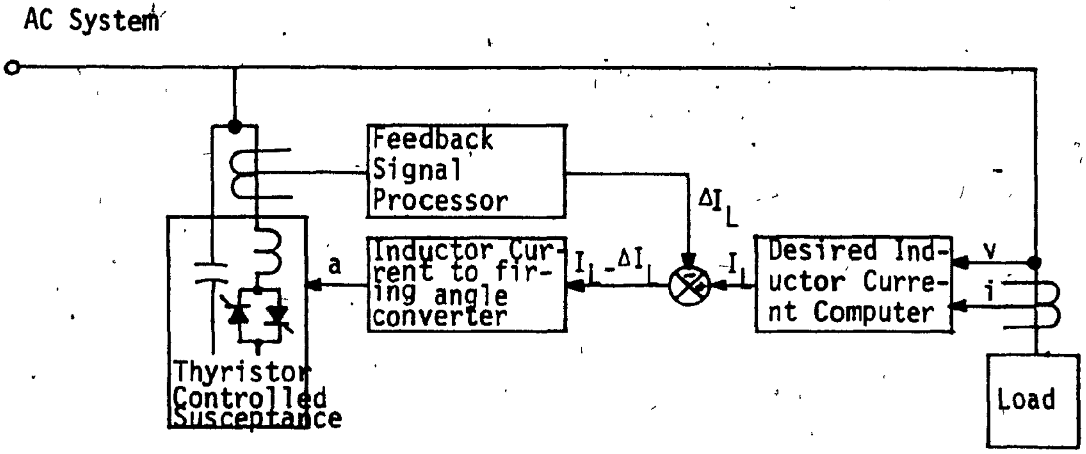


Fig. (3.9) USE OF NEGATIVE FEEDBACK IN AN OVERALL FEED FORWARD CONTROL SCHEME TO INCREASE THE ACCURACY OF THE INDUCTOR CURRENT TO FIRING ANGLE CONVERTER.

For example, the accuracy of the desired inductor current to firing angle conversion can be improved and made independent of circuit parameters by providing a negative feedback from the actual inductor current as indicated in fig. (3.9).

3.7 Dynamic Performance of SVS

Fig. (3.10), shows the simplified block diagram. The following simplifying assumptions were made:

- ΔV, voltage variation due to SVS remains small with respect to system voltage V;

- the system voltage deviates only slightly from rated voltage;

- the reference value V_{ref} is only varied in a small range around the system voltage.

Under these assumptions the following is valid;

$$Y_L = I_L \qquad Y_c = I_c \text{ in p.u} \tag{3.10}$$

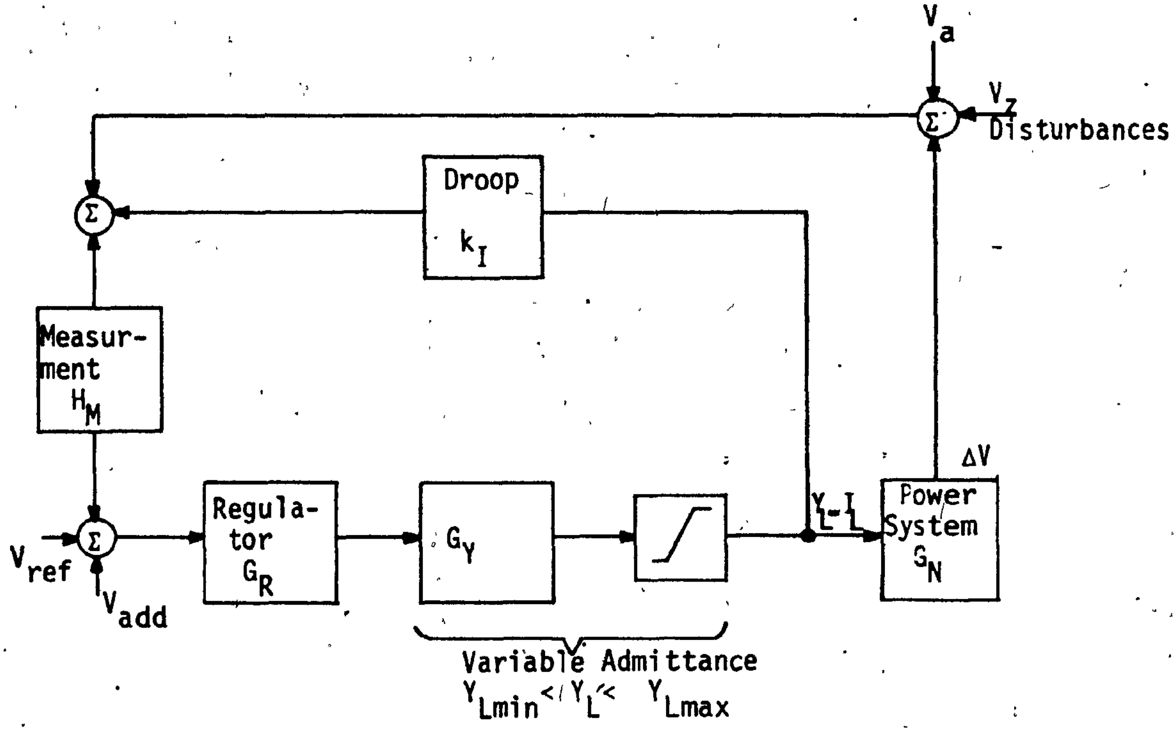


Fig. (3.10) SIMPLIFIED BLOCK DIAGRAM OF SYSTEM VOLTAGE CONTROLLER FOR $V \simeq V_{rated}$.

The constant droop influence of I_c is taken into account by the reference value V_{ref} thus only the influence of the inductive part I_L must be further considered. The current I_L reduces the no-load voltage V_0 of the system by ΔV. The influence of I_c on the system voltage is already included in V_0. The disturbance V_z is for the present zero.

From fig. (3.10), the behaviour for small signals around the rated voltage is explained. Due to the small SVS ratings of present installations with regard to the system fault level and standard droop settings of a few percent of the rated voltage, the above approximations are valid for the entire control range (normally covering a few percent around the rated voltage).(138)

3.8 Dynamic Performance of the Control Loop Elements

Fig. (3.11), illustrates the dynamic performances of the variable admittance Y_L described with the transfer function G_y. The absolute value of the vector I_L of the three-phase current system is calculated from the three inductive SVS currents, using the method shown on fig. (3.12). The value of I_L is a measure of the alternating currents i_{LA}, i_{LB}, i_{LC} and instantaneously follows their changes. For the tests Y_L was applied to an infinite bus, thus $I_L = Y_L$ is valid.

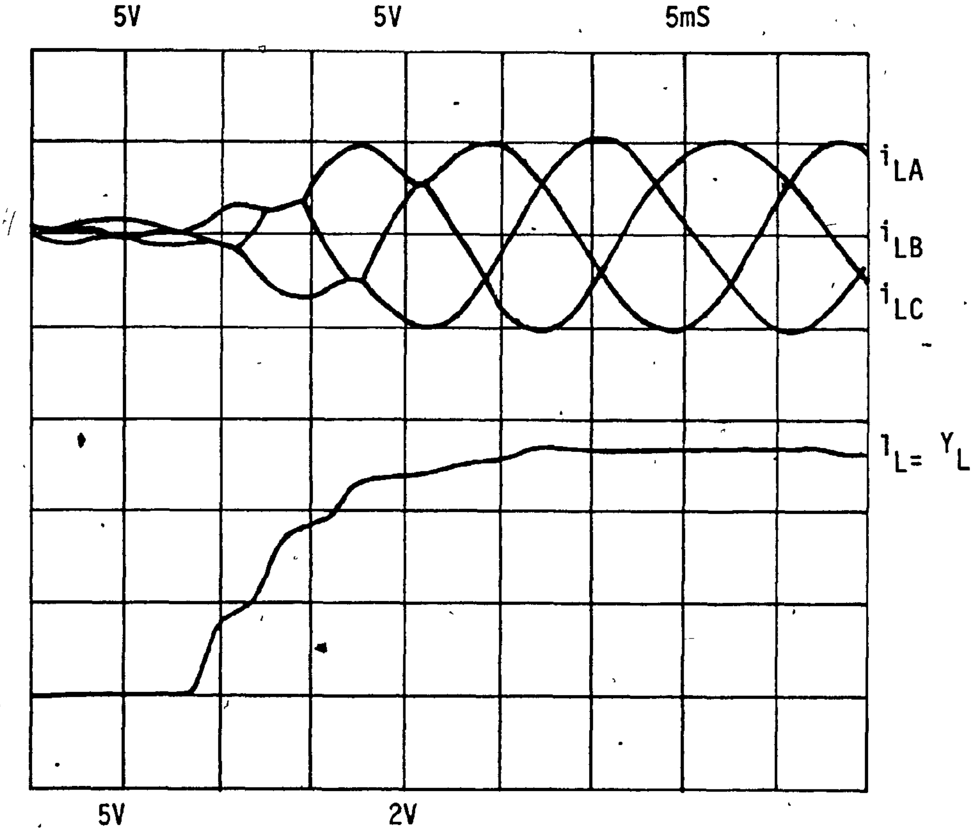


Fig. (3.11) STEP RESPONSE OF REACTIVE CURRENT I_L AND ADMITTANCE FOLLOWING A CONTROL VOLTAGE STEP ON THE INPUT OF G_y.

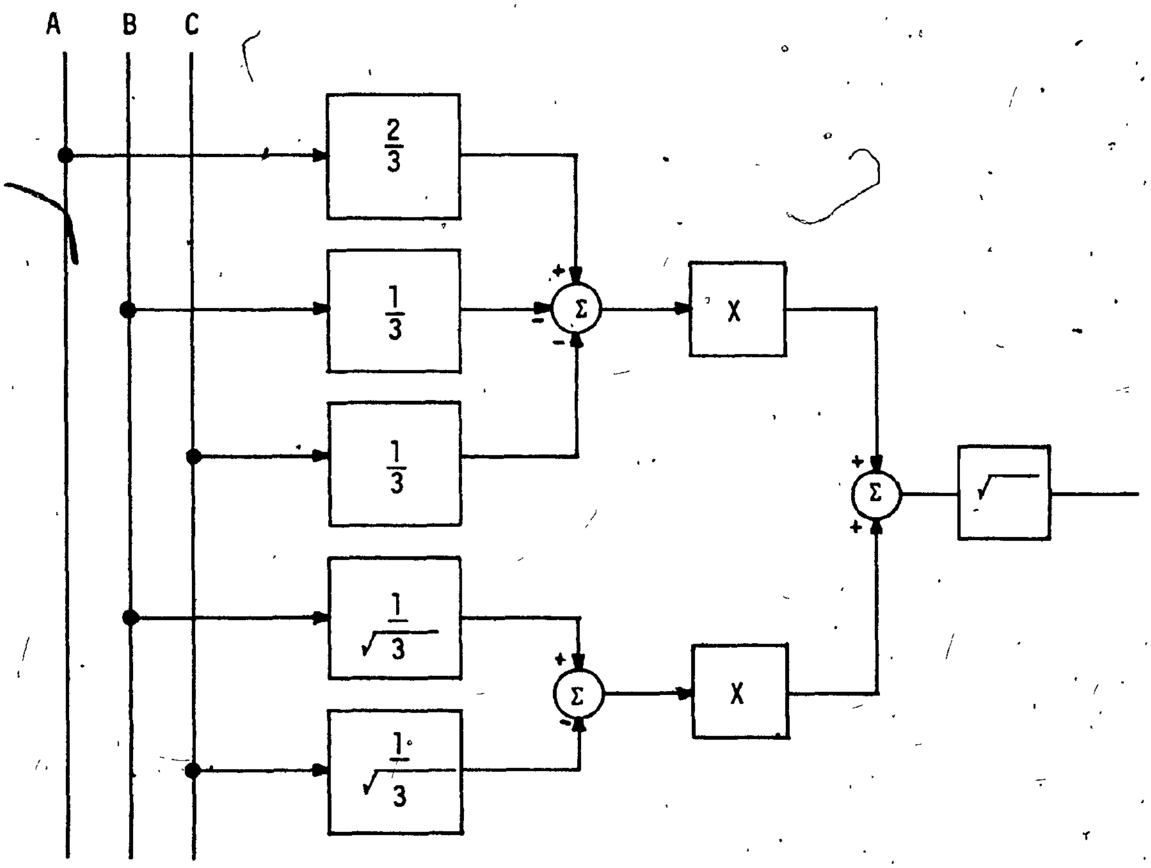


Fig. (3.12) VECTOR TRANSFORMATION METHOD FOR INSTANTANEOUS MEASUREMENT OF THREE PHASE ALTERNATING QUANTITIES.

Fig. (3.11), shows the characteristic $I_L = Y_L$ with respect to time after application of a step function of amplitude 1.0 p.u. on the input of G_Y. The upper three traces of the oscillogram show the three currents. It can be clearly seen that one cycle after the step the three currents have reached the new value, symmetrical and Y_L attained the stationary final value. The response can be well represented with a time constant of $T_Y = 5$ ms.

3.9 Influence of Power System on SVS Performance

The steady state and dynamic performance of an SVS are a function of certain performance of the ac system to which it is concerned. To understand what the properties are and how they effect the SVS performance, it is convenient to refer back to the control loop block diagram shown in fig. (3.5). In particular, the block labeled Z_{12} essentially represents the ac system through which this control loop is closed.

In power system short circuit studies it is sometimes useful to visualize the electrical network in terms of a matrix equation relating the bus voltages to current injections at the buses. That is, for an M-bus network, the voltages at the m-buses can be expressed in terms of the equation:

$$\begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ V_m \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots\cdots & Z_{1N} \\ Z_{21} & Z_{21}\ Z_{22} & \cdots\cdots & \cdot \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ Z_{m1} & & & Z_{mm} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ \cdot \\ I_m \end{bmatrix} \qquad (3.11$$

where the I_1, I_2 .... I_m are complex currents "injected" into buses 1 through m, respectively; the V_1, V_2 ...... V_m are complex bus voltage and the complex Z_{ij} elements are driving point and transfer impedances. Many of the injected current will be zero in a practical power network. Non-zero currents will exist where there are generators, loads, dc converters and static var supplies. Fixed shunt capacitors and reactors are generally lumped as part of the network impedance elements, Z_{ij}s.

Assume buses 1 and 2 of fig. (3.3a), are represented in the above equation. According to the eq. (3.11), the voltage V_2 on bus 2 is:

$$V_2 = Z_{21} I_1 + Z_{22} I_2 + \ldots\ldots\ldots Z_{2m} I_m \qquad (3.1$$

The contribution to V_2 attributable to the static var system on bus 1 is the first term in eq. (3.12), namely $\Delta V_2 = Z_{21} \Delta I$. Recalling that the impedance matrix is symmetric (in the absence of phase angle transfromers) then the change in V_2 which can be caused by a change in I_1 (or I_N) is:

$$\Delta V_2 = Z_{12} \Delta I_N \qquad (3.13)$$

The Z_{12} block in fig. (3.5), represents the entire ac system as viewed by the SVS in accordance with eq. (3.13).

The above mathematical development was based on a steady state, nominal frequency representation of the m-bus system in eq. (3.11). We can generalize the Z_{12} block in fig. (3.5), to include all dynamic properties of the system which could be visible to the SVS controls. The Z_{12} block then becomes an operational $Z_{12}(s)$ block where s is the familiar Laplace operator for d/dt in differential equations.

If a test were performed to determine the frequency response of the system at bus 1 the magnitude and phase of $Z_{12}(j\omega)$ could be obtained by injecting currents into bus 1 at a of frequencies (ω) and measure the magnitude and phase of the voltage at bus 2 at those frequencies. The ratio $V_2(\omega)/I_1(\omega)$ would yield the gain and phase of the $Z_{12}(s)$ block in fig.(3.5).

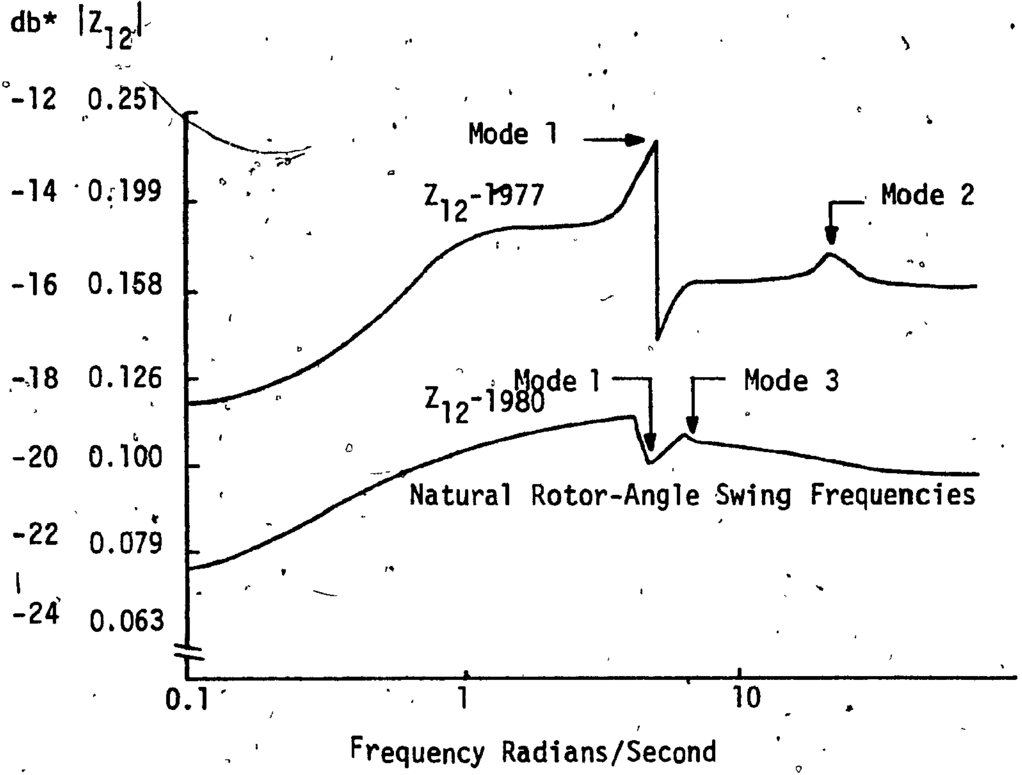
The magnitude of that transfer function is plotted in fig.(3.13), in which the curves are given for two different system conditions.

These plots illustrate two important points relative to the choice of voltage regulator characteristics. First, the natural frequencies (modes) of synchronizing power angle swings which are likely to be visible in the SVS supply voltage are evident in the plots.

The second observation is that the change in controlled voltage that can be accomplished through SVS regulator action varies with the speed of the requested change.

3.10.1 Power System Stabilization Via SVS Voltage Control

Various static devices for raising the stability limit of a power system exists. Among these devices are series capacitors, shunt capacitors, combined series and shunt capacitors and shunt static reactive compensators consisting of a fixed capacitor and a variable reactor.



* db = 20 $\log_{10} |Z_{12}|$

Mode 1 -All units swinging approximately in phase
Mode 2 -Natural Frequency of scotts bluff units
Mode 3 -Natural Frequency of Laramie River (East) unit

Fig. (3.13) FREQUENCY DEPENDANCE OF SYSTEM IMPEDANCE Z_{12}.

Stability improvement with these devices is accomplished in two basic ways.

1. Increasing the steady state power transfer capability, and
2. Enhancing transient (first swing) stability. Damping of power swings is feasible, but little or no experience exists with special damping controls. This section reviews the three subject areas mentioned, discussing in each case the SVS parameters important for stabilizing control.

3.10.2 Increasing Power Transfer Limits with Static Var Systems

The use of static devices to improve the power transfer capability and transient stability of HVAC system is not new. Synchronous compensators located at several places along a 600 mile HVAC line to assist in providing stable power transfer across that line. (139) The power transfer capability of a line section is limited by the phase angle between the voltage phasops and the two ends. The theoritical maximum transfer, would occur at $\delta = 90^0$ (140).

Fig. (3.14), represents an uncompensated line. The terminal

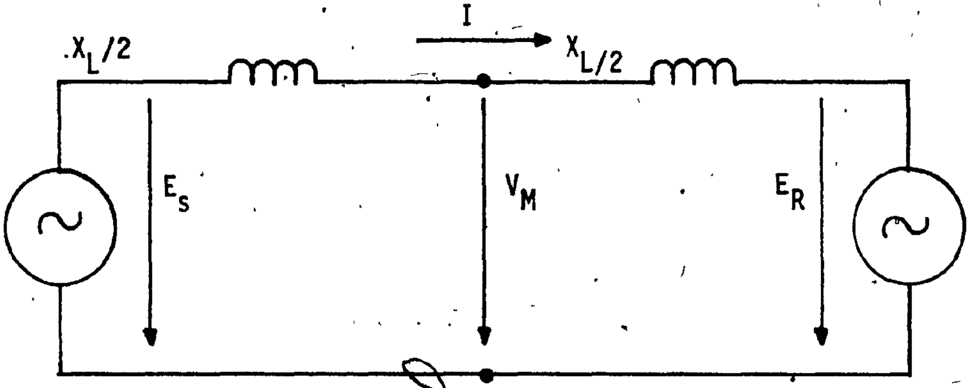


Fig. (3.14) CIRCUIT FOR CASE UNCOMPENSATED LINE voltages in this case are:

$$E_s = E \;\underline{|\delta/2} = E\;(\cos\frac{\delta}{2} + j\sin\frac{\delta}{2}) \qquad (3.14)$$

$$E_R = E \;\underline{|\delta/2} = E\;(\cos\frac{\delta}{2} - j\sin\delta/2 \qquad (3.15)$$

The midpoint voltage is:

$$V_M = V_M \;\underline{|0} = (E_s + E_R)\;/2 = E\cos(\delta/2) \qquad (3.16)$$

The current at both terminals and at the midpoint is:

$$I_s = I_R = I_M = I = \frac{E_s \;\; E_R}{j\,X_L} = \frac{2\,E}{X_L}\;\sin\;\frac{\delta}{2} \qquad (3.17)$$

Because of the assumed lack of loss, the power is the same everywhere. It is convenient to compute, is at the same midpoint, where the voltage V_M is in phase with the current I_M.

$$P = V_M\;I_M = \frac{2E^2}{X_L}\;\cos\;\delta/2\;\sin\;\delta/2 = \frac{E^2}{X_L}\;\sin\delta \qquad (3.18)$$

Maximum power occurs at $\alpha = 90^o$ and is:

$$P_M = \frac{E^2}{X_L}$$

The reactive power entering each terminal is:

$$Q_s = Q_R = EI \sin \delta/2 = \frac{2E^2}{X_L} \sin^2 \delta/2 = \frac{E^2}{X_L}(1 - \cos \delta) \quad (3.19)$$

That entering both terminals is:

$$Q_1 = 2Q_s$$

all of which is absorbed by the line:

$$Q_L = X_L I^2 = X_L \left(\frac{2E}{X_L} \sin \delta/2 \right)^2 = \frac{2E^2}{X_L} (1-\cos \delta) \quad (3.20)$$

Crary(139) found that practical values of machine reactance, when combined with the transformer reactance, would prevent a synchronous condenser from exercising ideally tight control of the HVAC bus voltage. Capacitors may be employed in series with the step up transformer to reduce that combined reactance to yield near-zero regulation of the HVAC bus voltage over the rated range of vars to approach the theoretical transfer capability.

3.10.3 Enhancing Transient Stability with Static Var Systems

Through aggressive control of the voltage at one or more points in an HVAC network, static var systems can assist generating units in developing synchronizing torque following a large disturbance such as a fault. Smaller first swing rotor angle excursions result thereby providing an additional margin of stability over the system without dynamic voltage support.

A convenient way to visualize the potential increase in transient stability margin due to intermediate voltage support is in terms of the power angle curves in fig. (3.16), and fig.(3.15) shows a two machine system with the terminal voltages E_1 and E_2 equal, and on intermediate voltage source fixed at E_s. The line is assumed to be lossless with a reactance of X_L and no charging. The intermediate voltage source is connected to the midpoint of the line through a reactance of X_s. Fig. (3.15b) shows a voltage-vs-reactive current characteristics for a SVS with a voltage regulation line of slope X_s and a no load virtual voltage of E_s

For an infinite value of X_s, the E_s source is ineffective, and we have the classical power angle ($R = \infty$) where $R=X_s/X_L$

The power is:

$$P_{12} = \frac{E_1 E_2}{X_L} \sin \delta_{12} \tag{3.21}$$

For an ideal reactive compensation with $X_s = 0$, the power

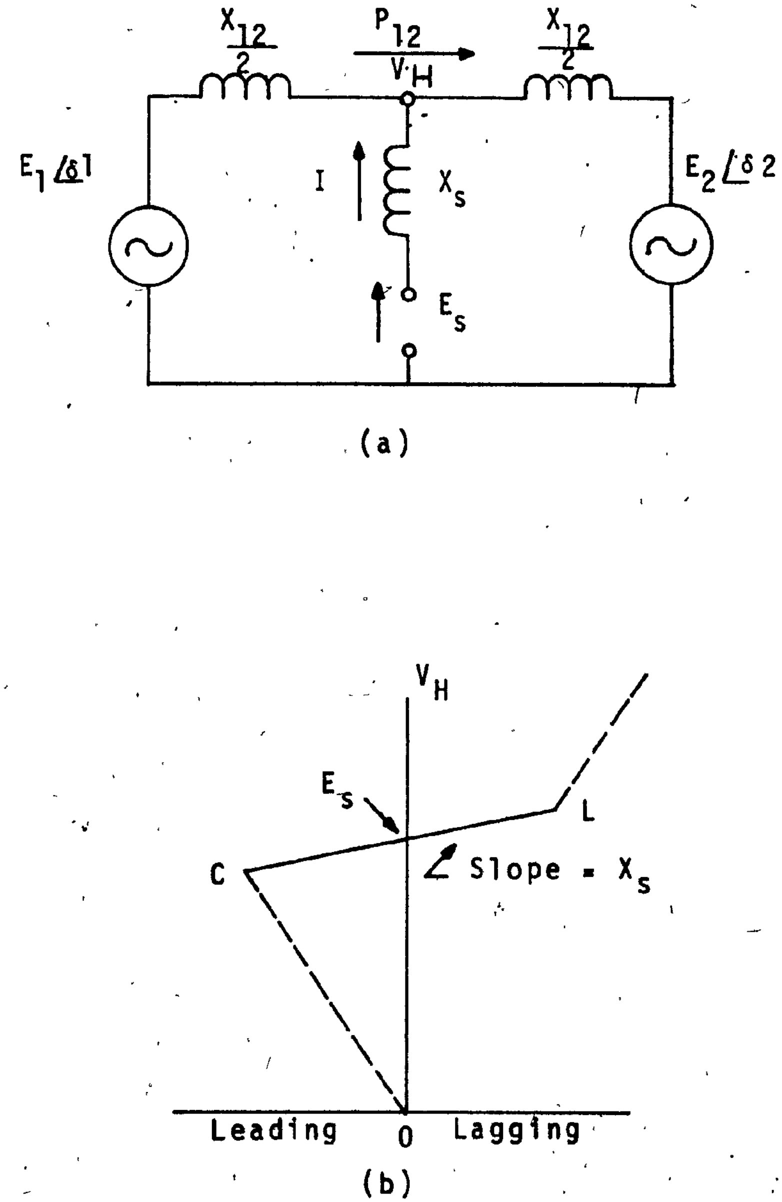


Fig. (3.15a) SHUNT REACTIVE COMPENSATOR WITH SOURCE E_s AND
(3.15b) SLOPE REACTANCE X_s AT THE CENTER OF LINE

angle in curve $R = 0$ applies. Then,

$$P_{12} = \frac{E_1 E_2}{X_L} \sin \frac{\delta_{12}}{2} \qquad (3.22)$$

For practical synchronous or static reactive compensators, some intermediate curve would apply. Then,

$$P_{12} = \frac{2}{4R + 1} \left(2R \sin \delta_{12} + \frac{E_s}{E} \sin \frac{\delta_{12}}{2}\right) \qquad (3.23)$$

with

$$R = X_s / X_L$$

and

$$E = E_1 = E_2$$

A family of curves with R as parameter is displayed in fig. (3.16). It is believed that all these curves drop to zero at $\delta = 180^0 = \pi$ radians. The reasoning supporting such belief is as follows. Let the Y connection of the three reactances be converted to a Δ, which is shown in fig. (3.17). If the three voltages are known, expressions for the power in each branch are easily written. The expression for the direct path SR is the first term of eq. (3.23), containing $\sin \delta_{12}$. The expression for the indirect path SKR is the second term of that equation, containing $\sin (\delta/2)$.

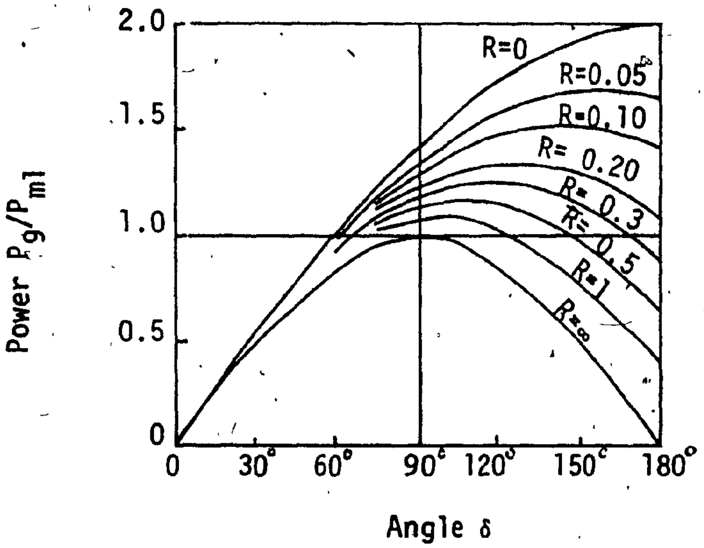


Fig. (3.16) FAMILY OF POWER-ANGLE CURVES.

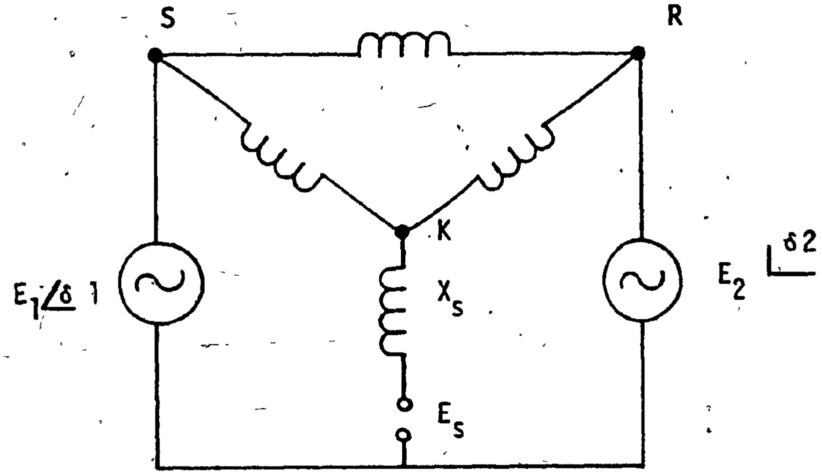


Fig. (3.17) EQUIVALENT DELTA REACTANCES.

The midpoint voltage (at terminals of compensator) this is given by the formula:

$$\frac{V_M}{E} = \frac{1}{4R - 1} (1 + 4R \cos \delta/2) \qquad (3.24)$$

plots are shown in fig. (3.18).

The lower the value of R, the less the voltage varies and the higher is the crest of the power-angle curve.

The reactive power furnished by the compensator is:

$$\frac{Q}{P} = \frac{4}{(4R+1)^2} \left[\left(\frac{E_s}{E}\right)^2 + (4R-1) \frac{E_s}{E} \cos \delta_{12/2} - 2R(1+\cos\delta_{12}) \right] \qquad (3.25)$$

A family of curves for various of R is plotted in fig.(3.19), with R=0, the reactive power is small at light load (small δ_{12}) and increases with δ_{12}.

Applying the equal area criteria, fig. (3.20), is constructed for a fault duration just long enough to give zero stability margin for a system without intermediate voltage support. Fig. (3.20b), was constructed with power-vs-angle curves consistent with expression in eq. (3.23), in fig. (3.16), and $0 < X_s < \infty$. The non-shaded area above the P_u line in

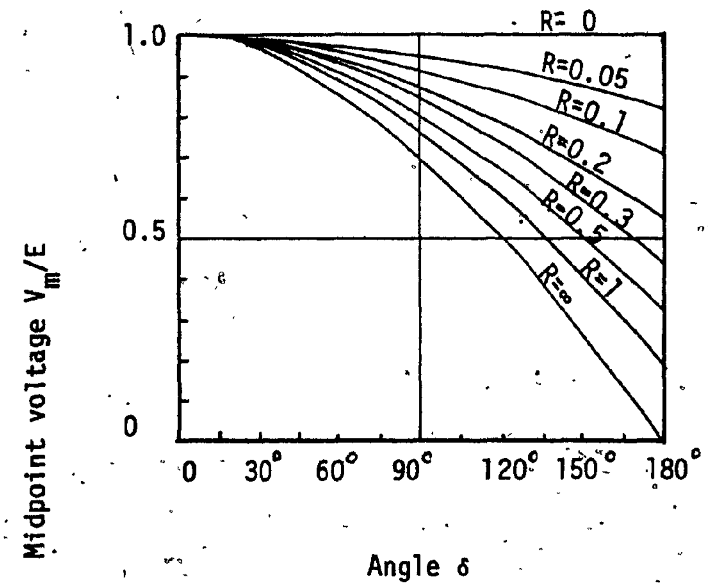


Fig. (3.18) FAMILY OF CURVES OF MIDPOINT VOLTAGE AS FUNCTION OF REACTANCE RATIO R AND ANGLE δ.

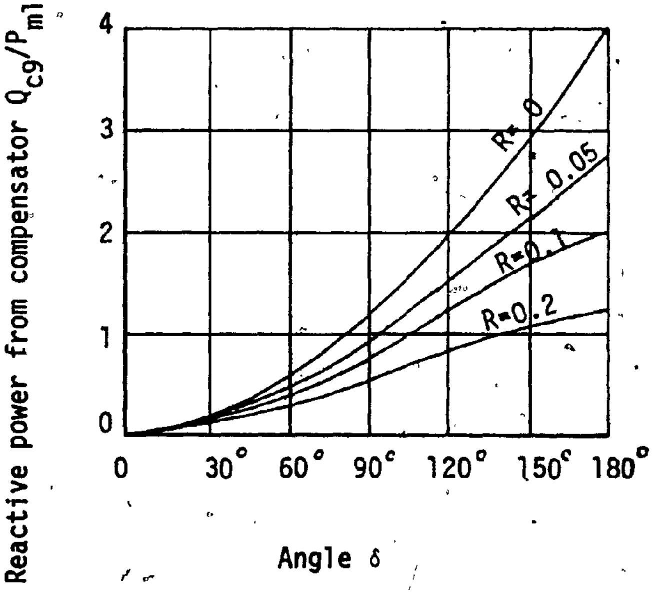


Fig. (3.19) REACTIVE POWER SUPPLIED BY SHUNT REACTIVE COMPENSATOR AS FUNCTION OF ANGLE δ AND REACTANCE RATIO R.

Fig. (3.20a)
without intermediate
Voltage support
($X_s = \infty$)

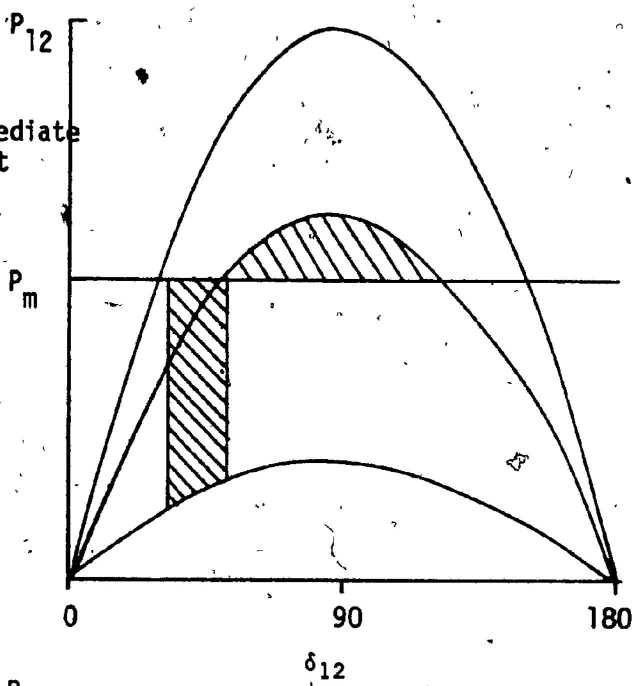


Fig. (3.20b)
with intermediate
voltage support
($0 < X_s < \infty$)

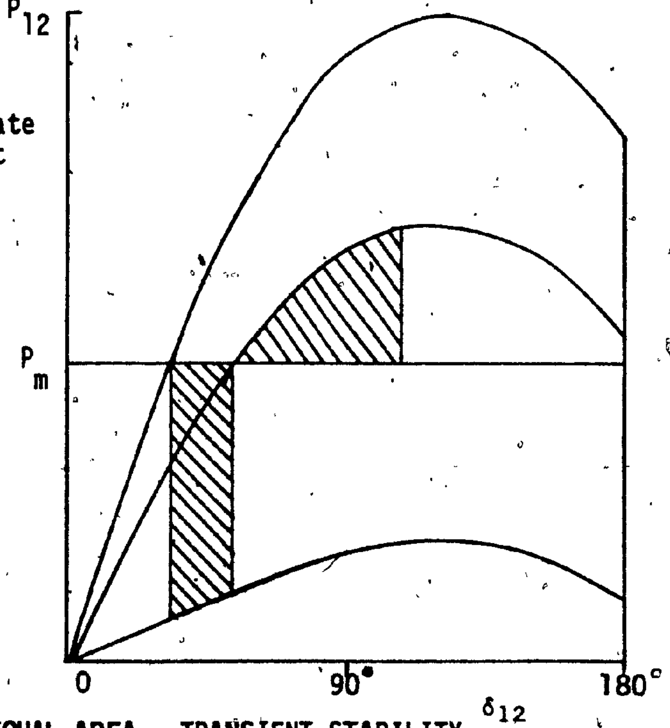


Fig. (3.20) EQUAL AREA TRANSIENT STABILITY
(3.20a) WITHOUT INTERMEDIATE VOLTAGE SUPPORT ($X_s = \infty$).
(3.20b) WITH INTERMEDIATE VOLTAGE SUPPORT ($0 < X_s < \infty$).

fig. (3.20b) is an approximate measure of the stability margin gained with the intermediate voltage support. The stability margin illustrated was attributable to a fixed voltage support E_s.

In reality, the voltages E_1, E_2 and E_s are constant over a period of the first swing is valid as a first approximation. The value of X_s then would be equivalent to the transient reactance of the synchronous condenser plus the transformer reactance.

For fig. (3.20b), to be valid for a static var system, the capacitive MVAR rating of the SVS must be sufficient so that leading current required at all times during the first swing is less than that corresponding to point c in fig. (3.15b). That current must be available at a reduced voltage. If the voltage V_H tends to drop below point c, then the SVS regulating range is exceeded and the SVS becomes a fixed capacitance. In like manner, should the voltage V_H rise above point L in fig. (3.15b), during the backswing, the SVS becomes effectively a fixed inductor.

The dashed lines in fig. (3.15b) represent operation outside of the rated SVS regulating range.

3.10.4 Damping of Power Swings

Exercising voltage control at strategic locations in a transmission, whether with synchronous or static compensation, will affect both synchronizing and damping torques of the supply generators.

Because the SVS can respond faster than its synchronous counterpart, the system can be operated closer to the steady state limit with the SVS. Furthermore, the SVS, because of its inherently smaller effective time constant, will track power swings on the line more closely than the synchronous condenser. Voltage swings at the system midpoint cuased by oscillations in power would be damped more by the SVS but power swings may go undamped.

The SVS controls could be modified, or the voltage error fed to the SVS regulator could be augmented to provide some damping of power swings,(121) if there is a predictable pattern of power flow in the network as viewed from the SVS site. Bus frequency, line power, or line current might be sensed, phase shifted and added to the voltage error of the SVS regulator to cause SVS control to damp out swings in the line power flow.

Theoretically this concept is similar to the concept of the power system stabilizer used with voltage regulators on synchronous generators. Power swing damping with an SVS has not been studied or demonstrated to the extent speed or power-derived stabilizers on generator excitation systems has been demonstrated. This concept may yield some incremental stabilizing benefit to system utilizing SVS's to stabilize long transmission systems with uni-directional power flow such as those fed by large remote mine-mouth generating plants.

CHAPTER IV

PERFORMANCE MODELING OF S V S

4.1 Introduction

This chapter provides design and modeling information on the representation of static var systems. Three types of static var systems were described in chapters 2 and 3. The thyristor-controlled reactor (TCR) and thyristor-controlled transformer (TCT) types are very similar, therefor the modeling of their steady-state and dynamic performance are treated together. The thyristor-switched capacitor (TSC) type of S V S differs from the TCR and TCT types so references on the dynamic modeling of the TSC are cited.

Information and data are provided in such a format as to permit application to commonly utilized digital and analog programs and models.

The S V S is a relative newcomer to the utility planner's repertoire of voltage/var compensating capabilities. In order for the utility planner to assess the usefulness of a S V S in his sytem and compare its performance with alternate forms of compensating means, he must conduct performance studies.

4.2 Steady-State Performance

The modeling of the TCR, TCT and TSC type static var systems for power flow studies is conceptually the same.

An important distinction to remember is that the static var system is not a source of generated voltage as is a generator or synchronous condenser. Synchronous machines actually generate a voltage by varying the electromagnetic flux linkages of a coil in the air gap. The S V S, instead, varies the voltage by varying the flow of reactive current through an effective system impedance. That current still must be supplied by generators elsewhere on the system.

S V S are used to control the transmission voltage at a given terminal and to provide power factor correction. Two types of compensation problems are normally encountered in practical applications. The first is load compensation where the requirements are usually to reduce or cancel the reactive power (var) demand of large and fluctuating industrial loads, such as electric arc furnaces, rolling mills, etc.., and to balance the real power draw from the ac supply lines. These types of heavy industrial loads are normally concentrated in one plant and served from one network terminal, and therefore can be handled best by a local compensator connected to the same terminal.

The second type of compensation is related to the voltage support of a transmission line at a given terminal in the face of disturbances of both loads and generation. Here the load is localized; several areas and generator units may be tied by a transmission network and the objective is simply to regulate the voltage at the compensated terminal.

Several types of static compensators with different operating futures can be realized using various power conversion concepts and thyristor circuits.(141) In this chapter only the variable impedance types, that is those which essentially function as variable reactances (capacitive and inductive impedances), are considered.

There are usually two main reasons for compensating large, fluctuating loads:

1. the ac system is too weak to maintain the terminal voltage with acceptable variations and,

2. it is not economical, or practical, to supply the reactive power demand from the ac system. Load compensation thus tends to reduce the undesirable effects of a single load (or load group) on the ac system, without attempting to change the external regulation of the terminal voltage. (This is in contrast to transmission line voltage support, where the compensator is employed to reduce terminal voltage variation regardless of its cause.)

The primary interest at a terminal of a transmission line is generally the voltage because;

1. it determines the available or transmittable power, and

2. it may have to meet some quality requirements for consumers.

For this reason, transmission network compensation requires a different approach than load compensation.

4.3 Transmission Line Voltage Support

Consider a general network compensation problem illustrated schematically in fig. (4.1). A number of transmission lines

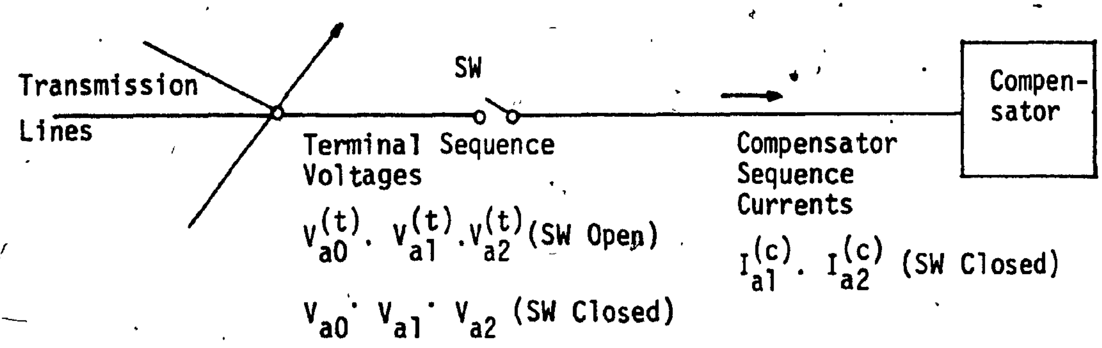


Fig. (4.1) A GENERAL TRANSMISSION NETWORK TERMINAL WITH A COMPENSATOR are tied together at a terminal, the voltage of which is to be regulated and balanced. Generators as well as loads may be connected to each transmission line.

The voltages at the terminal are generally unbalanced, comprising zero, positive, and negative- sequence components, which will be denoted by:

$$V_{ao}^{(t)}, \; V_{a1}^{(t)}, \; V_{a2}^{(t)} \qquad (4.1)$$

Consider a general ungrounded three-phase load represented by impedances Z_a, Z_b, and Z_c, connected to the terminals of an ac system with a set of symmetrical line to neutral voltages:

$$V_a = V$$

$$V_b = V_e^{-j2\pi/3} \qquad \text{and}$$

$$V_c = V_e^{-j4\pi/3}$$

as shown in fig. (4.2a). The delta equivalent of the load represented for convenience, by admittances Y_{ab}, Y_{bc}, and Y_{ca} is shown in fig. (4.2b). Impedances Z_a, Z_b, Z_c (or admittances Y_{ab}, Y_{bc}, Y_{ca}) are in general functions of time.

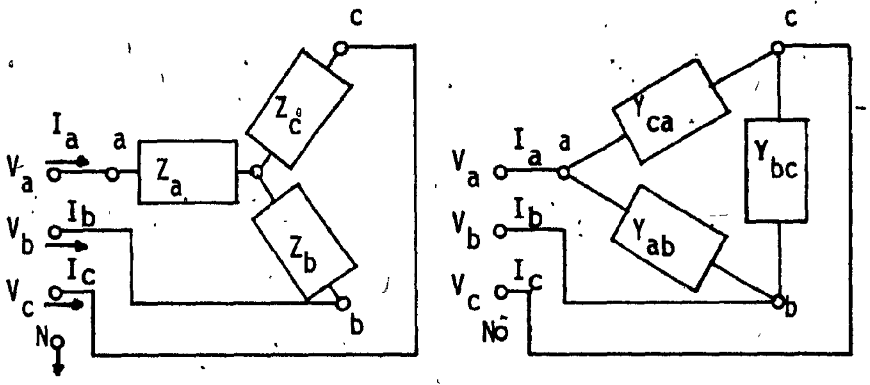


Fig. (4.2a) GENERAL THREE-PHASE WYE CONNECTED LOAD REPRESENTED BY IMPEDANCES

(4.2b) DELTA EQUIVALENT REPRESENTED BY ADMITTANCES.

In order to establish the basic compensation requirements it will be assumed that the three load impedances are time-invariant and different from each other, that is, they represent a general steady state unbalanced load. This assumption does not exclude the eventual consideration of time varying impedances.

The compensation problem becomes that of finding a reactive admittance network which when combined with the load admittance will present a real and balanced load to the supply terminal.

Using the delta equivalent representation of fig. (4.2b), the three load admittances can be compensated separately as if they were three signle-phase loads. Consider for example phase ab. If admittance Y_{ab} is composed of a real component (conductance) and reactive component (susceptance) that is:

$$Y_{ab} = G_{ab} + j\,B_{ab} \tag{4.2}$$

the reactive part can, as a first step of the compensation be cancelled by an appropriate compensating susceptance, $-B_{ab}$, connected in parallel with Y_{ab} as illustrated in fig. (4.3).

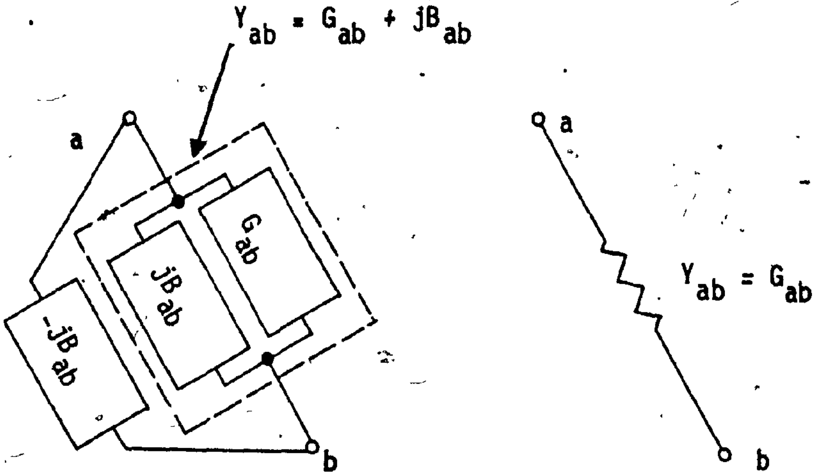


Fig. (4.3) COMPENSATION OF THE REACTIVE PART B_{ab} OF ADMITTANCE Y_{ab} BY SUSCEPTANCE $-B_{ab}$.

As a second step of the compensation, real admittance G_{ab} has to be complemented with a reactive admittance network so as to obtain a resultant balanced load on the ac supply.

The compensation can generate positive-sequence reactive current component I_{a1}, and negative-sequence current component I_{a2}. The zero-sequence compensator current I_{a0}, is zero because of delta configuration. Thus the compensator is unable to influence directly the zero-sequence terminal voltage.

The symmetrical components of the voltage at the network terminal, with the compensator connected (SW closed), can be expressed in terms of the current components of the compensator and the original terminal voltages as follows:

$$V_{a1} = V_{a1}^{(t)} - Z_{11} I_{a1}^{(c)} - Z_{12} I_{a2}^{(c)} \qquad (4.3)$$

$$V_{a2} = V_{a2}^{(t)} - Z_{21} I_{a2}^{(c)} - Z_{22} I_{a2}^{(c)}$$

where Z_{11}, Z_{12}, Z_{21}, and Z_{22} are the symmetrical component impedance coefficients of the network.

With eq. (4.3) the objectives of the compensation may be stated as follows:

1. Eliminate the negative-sequence voltage
2. Stabilize the positive-sequence voltage at the terminal.

Mathematically this means that:

$$V_{a2} = 0 \tag{4.4}$$

$$|V_{a1}| = V = \text{constant} \tag{4.5}$$

Equation (4.3), can be solved for I_{a1} and I_{a2}, and with the subsequent use of eqs. (4.4), and (4.5), the sequence currents required for compensation can be specified thus:

$$I_{a1}^{(c)} = Y_{11}\,(V_{a1}^{(t)} - V_{a1}) + Y_{12}\,(V_{a2}^{(t)} - V_{a2}) \tag{4.6}$$

$$I_{a2}^{(c)} = Y_{21}\,(V_{a1}^{(t)} - V_{a1}) + Y_{22}\,(V_{a2}^{(t)} - V_{a2}) \tag{4.7}$$

where Y_{11}, Y_{12}, Y_{21}, and Y_{22} are the symmetrical component admittance coefficients corresponding to impedance coefficients Z_{11}, Z_{12}, Z_{21}, and Z_{22}. With the substitution of eq. (4.4), eqs. (4.6), and (4.7), become:

$$I_{a1}^{(c)} = Y_{11}\,(V_{a1}^{(t)} - V_{a1}) + Y_{12}V_{a2}^{(t)} \tag{4.8a}$$

$$I_{a2}^{(c)} = Y_{21}\,(V_{a1}^{(t)} - V_{a1}) + Y_{22}V_{a2}^{(t)} \qquad (4.8b)$$

Equation (4.8), gives a general relationship between the compensating sequence currents, the symmetrical component admittance coefficients and the sequence voltages of the ac system terminal.

Inspection of these equations suggests immediately that they would not, in general, provide a useful basis for any practical control approach. The primary reason for this is that the admittance coefficients of the ac system, in which load and generation changes may occur, are not known and cannot be measured.

Similar difficulties exist with terminal sequence voltages $V_{a1}^{(t)}$ and $V_{a2}^{(t)}$.

Despite the impracticability of eqs. (4.8), they are helpful in understanding the problem of terminal voltage compensation and, for this purpose, they will be further investigated.

The fist question is whether eqs. (4.8), are soluble at all under restriction that the positive-sequence compensating current $I_{a1}^{(c)}$ must be purely reactive, that is:

$R_e I_{a1}^{(c)} = 0$. Let $I_{a1}^{(c)}$ be given by:

$$I^{(c)} = jB_p^{(c)} V_{a1} \qquad (4.9)$$

where

$$B_p^{(c)} = B_{ab}^{(c)} + B_{bc}^{(c)} + B_{ca}^{(c)} \quad \text{from eq. (4.8a).}$$

$$V_{a1} = \frac{Y_{11} V_{a1}^{(t)} + Y_{12} V_{a2}^{(t)}}{jV_p^{(c)} + Y_{11}} \qquad (4.10)$$

Since the numerator of the right-hand member of eq. (4.10), is constant (a complex number), the magnitude, $|V_{a1}|$, of sequence voltage V_{a1} varies with the compensating susceptance $B_p^{(c)}$ (or equivalently, with the positive-sequence compensating current $I_{a1}^{(c)}$. Therefore the condition $|V_{a1}|$ = constant { eq. (4.4)})can be satisfied.

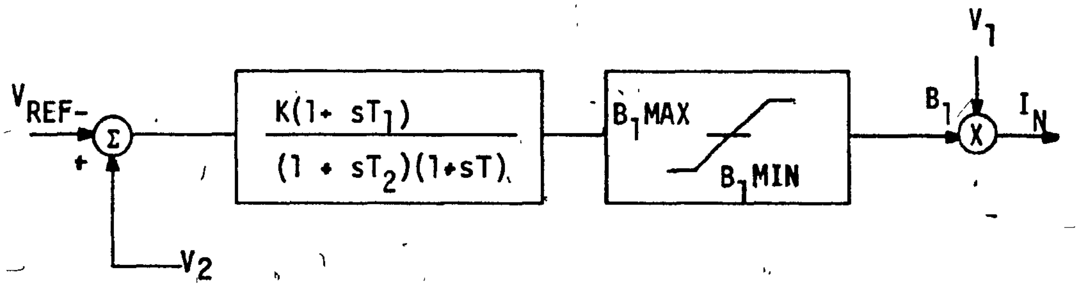
4.4 Modeling the SVS for Stability Studies

Stability, i.e., the ability of various parts of the system to remain in synchronism following disturbances, is a very important aspect of power system performance. The main dynamic effects concern the exchange of kinetic energy between machine rotors through power conversion from mechanical to electrical and vice-versa. The phenomena are characterized by power swings between groups of generators with typical periods between o.5 sec. and 5 sec.(52-107).

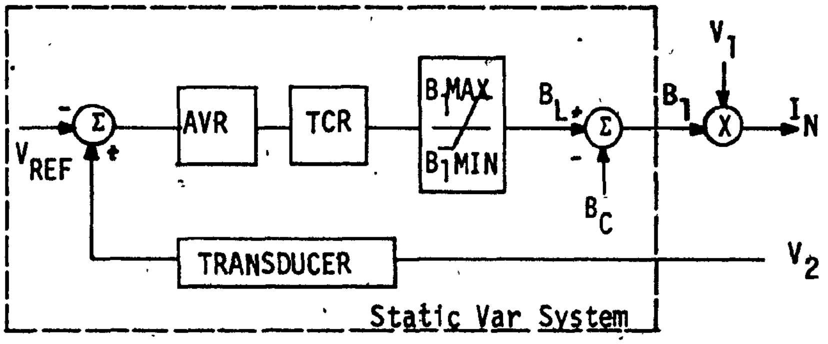
The static var system can be modeled as a time varying shunt reactance (or admittance) for conventional stability studies. Those studies are concerned with positive-sequence system behavior where frequency does not vary greatly from 60 (or 50) hertz. To that end, the block diagram in fig. (4.4a), can be utilized to model a SVS (113). Fig. (4.4b), is a similar block diagrm tailored to the TCR type of SVS configured as in chapter III, fig. (3.3).

More specific models have been suggested by the leading suppliers of the TCR, TCT and TSC static var systems (113). The general model in fig. (4.4b), will suffice for most balanced, fundamental frequency dynamic studies. Due to the author's familiarity with the TCR types SVS, the rest of this section will refer to modeling that kind, for which the models of fig. (4.4a), and (4.4b), are equivalent. Much of the discussion would apply equally well for the TCT type, but the TSC model is best described in the ref. (108, 113).

The contents of the dashed box in fig. (4.4b) represent the static var system with the output of the model representing the time varying shunt admittance of the parallel



(a)



(b)

Fig. (4.4) SVS MODELS FOR DYNAMIC STUDIES
(4.4a) GENERAL MODEL FOR ALL SVS TYPES
(4.4b) MODEL OF TCR

L and C in chapter III, fig. (3.3).

The model shown includes a voltage transducer which measures V_2 on bus 2, a comparator which subtracts the setpoint, V_{ref}, from the measured V_2, the AVR (voltage regulator), the TCR and the admittance of the controlled reactor, B_L. The capacitor is represented by a constant capacitive admittance, B_c. The net admittance on bus 1 is the difference $B_1 = B_L - B_c$.

The choice of automatic voltage regulators is even more variable since it is here where the SVS designer can exercise innovative license to optimize the SVS dynamic performance. A general representation recommended for the AVR is:

$$AVR = \frac{(1 + T_{1s})}{(1 + T_s)} \cdot \frac{K}{(1 + T_{2s})} \qquad (4.11)$$

where K = gain of AVR amplifier

T = a basic time constant chosen to limit band-width

T, and T_2 are time constants used to tailor the regulator performance for control stability.

The value of gain K, must be chosen consistent with the desired voltage control range ($e_1 + e_2$ or 2_e) and the short circuit capacity of the system measured at bus 2 without the SVS connected. Values of 100 to 400 are typical for k but it is recommended that the particular supplier be consulted for the correct selection.

All control circuit models within the TCR and AVR block must not suffer control error windup for periods during the simulation when B_L is in limits at either a maximum or minimum value. When operating in B limits, the controller blocks should be forced to cease changing their outputs in response to continuing existence of an error.

4.5 Modeling of SVS for Transient Conditions

In addition to inclusion in load flow and power frequency dynamic phenomena most transmission system equipment must also be modeled in studies of transient overvoltages due to switching faults, etc.., and for dynamic phenomena other than at power frequency, e.g., for studying the effect of SVS on reaction to subsynchronous responses caused by series capacitors.

The modeling of conventional transformers and reactors for transient problems is a rather specialized task.

The following paragraphs will discuss the techniques for modeling conventional devices and then comment on specific extensions of these modeling methods to SVS. There are basically three methods for modeling reactive devices to predict reponse to transient problems. They are:

1. Physical (scaled) models
2. Analog models
3. Digital models

4.5.1 Physical (Scaled) Models

The most usual way of studying reactive devices on systems is the construction of small physical models for interconnection with similar scaled representation of other system elements, including transmission lines, capacitors, etc. This modeling uses the basic rules of similitude, which require that all of the fundamental dimensions inherent in the actual device (length, voltage, impedance, etc.) be scaled in a mutually compatible way, or at least that those which failed to adapt to proper scaling can be shown to be insignificant to the phenomenon being studied.

Transformers or reactors whose rating may be in hundreds of MVA are commonly modeled by scaling the power base down to the order of 100 MVA, being careful to duplicate power frequency saturation characterisitics, turns ratio, etc. In making such reduction of scale, it is possible to keep all dimensions reasonably consistent except for resistivity.

Although it is theoretically possible to model distributed capacitance in a scaled-down transformer, the capacitance from windings to ground and between windings is usually ignored on the basis that it is not critical to most problems studied.

It is difficult to satisfy all of these modeling concerns and still reduce the power base to one that is compatible with most digital models (TNA).

4.5.2 Analog Models

One way to circumvent the physical limits cited in the above paragraph is to represent a device by diffrential equations rather than a physical structure. These differential equations can then be represented either digitally or on an electronic differential analyzer. The latter technique has been succesfully used to model both the physical characteristic of an SVS, as well as the control system for it. But the use of an electronic differential analyzer for extensive representation of the surrounding system in three-phase forms is often difficult.

4.5.3. Digital Models

For the same reasons of complexity and variability in SVS control design it would be prohibitive to model an entire SVS in a transient network analyser.

Digital modeling of the performance equations of a reactive device on SVS has certain advantages over the analog model in many cases.

However, the thyristors, reactors, capacitors, transformers and the rest of the ac supply system can be represented with conventional TNA apparatus and the actual SVS control can be interfaced to the model thyristors. With such a model system, the performance of the SVS in the face of switching transients and lightning strikes can be simulated.

The oscillograph traces shown in fig. (4.5), were obtained from just such a simulation set-up on the TNA. The study was made to assess the benefits of using an SVS at the terminal of an HVDC link. The chart shows (from top to bottom) the feedback or transducer signal-positive downward-

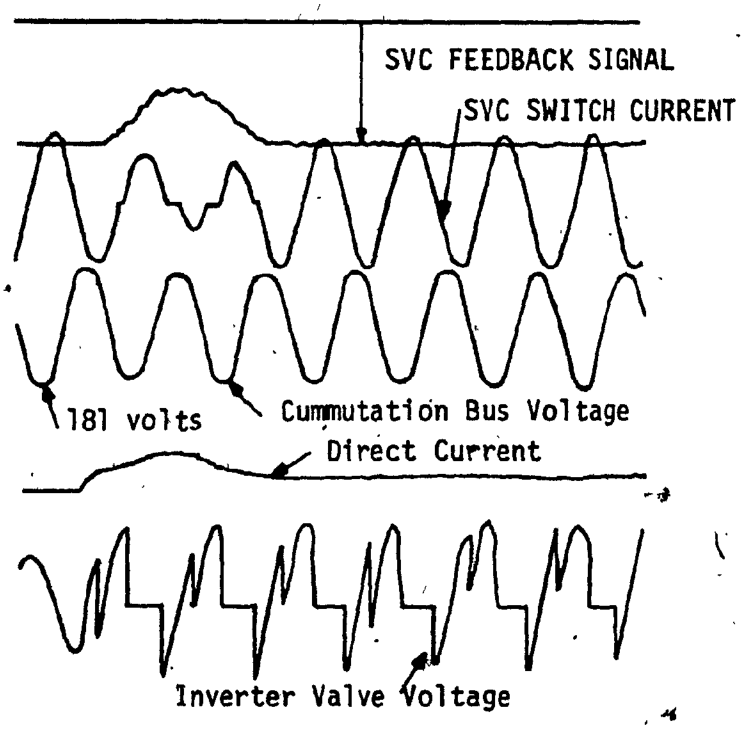


Fig. (4.5) OCILLOGRAPH FROM A TNA SIMULATION INVOLVING AN SVS AND AN HVDC LINK.

followed by the current in the thyristor switch and inductor. The trace labeled commutation bus voltage corresponds to voltage V_2 in chapter III fig. (3.3), which was also the commutating bus for an HVDC inverter terminal in the TNA set-up. The direct current in the HVDC link and the voltage across the inverter values are also shown. The trace of direct current shows that the simulation was addressing a DC start-up sequence.

4.6 New Designs

A new type of thyristor controlled shunt var compensator has been presented by the University of Manitoba (UM-Concept)(142). In that design the authors discovered that the existing designs represent one extreme whereas the first design of the authors was the other extreme of a wide range of design possibilities that exist to pick a real optimum configuration.

The novelty of the proposed new concept can best be demonstrated by examining the schematic diagram of fig.(4.6). The required reactance X is split into two, each of value 2X. A thyristor is used in each arm such that each of the paralleled branches has a reverse biased thyristor. The operation of this circuit is not different from the designs discussed in chapters II, III, Iv for $90 \leq \alpha \leq 180$. However,

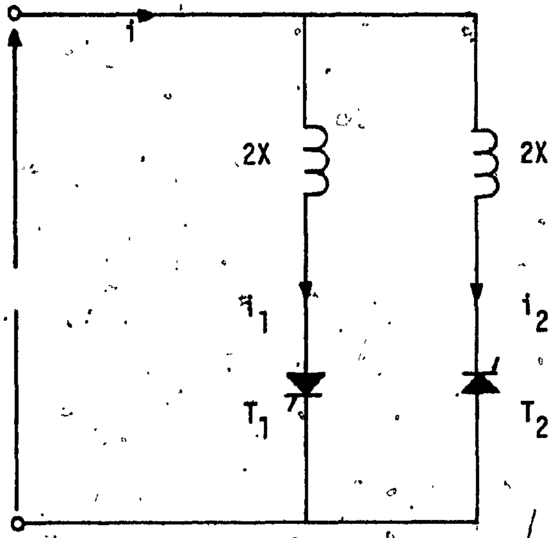


Fig. (4.6) BASIC REALIZATION OF THE UM-CONCEPT.

it is now possible to operate the circuit at any value of α from 0^o to 180^0. For $0 \leq \alpha \leq 90$ there are periods when both thyristors of a circuit (per phase) conduct, thereby, causing a circulating current in the paralled branches.

Reference (142) presents a general analysis for the computation of currents and voltages of various components.

FUTURE TRENDS

In both HVDC and SVS systems, the trend is toward higher power ratings. In order to achieve higher ratings and at the same time reduce the cost per megawatt, it is necessary to use higher rated thyristors. As indicated earlier, the largest thyristors currently in use on commercial projects are 53mm in diameter. Development work on larger devices with appropriate performance characteristics has continued In 1977, 77mm devices with ratings of 3,800 V and 1,600A are expected to be ready for commercial installation. By 1982, devices 100 mm in diameter should become available. Higher voltage thyristors, rated 5000V and above also are close to realization.

For many years, high voltage thyristor equipment designers have been interested in the possibility of using direct light-fired high power thyristors. The availability of such devices would make it possible to eliminate a major portion of the gating circuitry within the valve or thyristor controller and, thereby reduce the cost and increase the reliability. Recognizing the potential benefits of such a device, in 1975 EPRI awarded contracts to General Electric and Westinghouse to develop direct light-fired thyristors. The concept being pursued by General Electric is the incorporation of a double amplifying gate in the center region of an existing power thyristor. The use of two stages of amplification substantially reduces the amount of light required and also makes it possible to preserve the existing parameters (di/dt, dv/dt, etc..) of the main thyristor.

Another potential means for achieving a cost reduction in high power thyristor equipment is the utilization of improved cooling methods. Sigle-phase liquid cooling systems, using freon or water, are being developed by several manufacturers.

In addition, forced vaporization (two-phase) cooling has been proposed as a means for fruther reducing the thermal resistance between the heat sink and the ambient.

However, before this cooling means can become a reality, studies are necessary to determine the dielectric properties of the two-phase medium and the effects of non-condensible gases in the liquid on the heat transfer.

CONCLUSION

This report has discussed a broad class of problems concerning the control of voltage vars. The more common devices and schemes utilized to solve these problems were also discussed.

Also has reviewed the steady state and dynamic performance of thyristor-controlled static var systems in terms of fundamental concepts.

Furthermore, the modeling of static var systems involving the use of thyristors-controls was discussed. Digital modeling concepts were described for the conventional power flow and stability study programs used broadly by utility planners. Validation of these modeling concepts is in progress at the time of this writting and future papers will be devoted to any refinement of the models found necessary based on field test and experience.

The emergence of the static var system provides the utility planner with a very powerful voltage and voltage aid. Some of the unique performance features of the SVS will nodoubt be the im[illegible]ce to planner and operator alike, as they face the need to transport more power over longer electrical distances with minimal investment in new transmission equipment.

APPENDIX A

A.1 Derivation of Block Diagram in Fig. (3.4b).

Eliminating the multiplier in fig. (3.4a) can be accomplished by linearizing $I_N = B_1 V_1$ about the operating point B_o, V_o. Therefore:

$$\Delta I_N \approx B_o V_1 - V_o \Delta B, \tag{A.1}$$

Since the effect of other current sources on V_2 (dashed arrow in fig. (3.4a) is small then:

$$\Delta V_2 \approx \Delta I_N Z_{12} \tag{A.2}$$

$$\Delta V_1 \approx \Delta I_N Z_{11} \tag{A.3}$$

where Z_{11} and Z_{12} are self and transfer impedance of the system without the SVS capacitor or reactor connected to bus. 1, eq. (A.3) can be written as:

$$\Delta V_1 \approx \Delta I_N \ (Z_{12} + X_t) \tag{A.4}$$

where I_N is reactive only, poritive for leading current, and X_t is the transformer reactance.

Substituting eq. (A.2), (A.3) and (B.4), into (A.1), yields:

$$\Delta V_2 = Z_{11} B_o \Delta V_2 - Z_{12} V_o \Delta B$$

from which solving for $\Delta V_2 / \Delta B_1$ gives:

$$\Delta V_2/\Delta B_1 = \frac{V_o Z_{12}}{1 - B_o Z_{11}}$$ used in fig. (3.4b)

A.2 Computation of Regulator Gain, K.

The steady state error of the system in fig. (3.4b), following a step of reference, V_{ref} can be shown to be:

$$e_{ss} = \Delta V_{ref} / (1 + KZ)$$

where KZ is the low frequency loop gain.

To maintain less than .055 p.u. error, KZ must satisfy:

$$KZ \geq \left(\frac{V_2 max}{.005} - 1 \right) \qquad (A.5)$$

where K = dc gain of AVR

$$Z = \frac{\Delta V_0 Z_{12}}{1-B_0 Z_{11}} \qquad (A.6)$$

$\Delta V_2 max$ = max. contribution to ΔV_2 possible through SVS control.

V_0 = initial per unit voltage on 13.8 kv bus.

B_0 = net admittance of SVS at initial operating point.

Z_{11}, Z_{12} = self and transfer impedance from eq. (A.2), (A.3).

ΔV_2 max was estimated by computer simulation of the system to be .07 per unit corresponding to a full range excrusion of the SVS inductor current. Therefore the product KZ had to exceed (.07/.005)-1 or 13 (23 db) to satisfy the ±.005 per unit steady state accuracy criteria.

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