THYRISTOR CONTROLLED
STATIC PHASE - SHIFTER: A NOVEL DESIGN

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ABSTRACT

Advantages of static phase-shifters over on-load tap-changer phase-shifting transformers are discussed. Two concepts of generating phase-quadrature voltage component by thyristor phase-control for producing a phase-shift are discussed in detail. Of the two concepts, based on the experimental investigations, the better one is chosen for presenting the details of the theoretical investigations. The amount of phase-shift angle required is calculated from fundamental components of the two voltages. A simplified theoretical method is used to calculate various currents and voltages in a system using a phase-shifter. Two different sets of theoretical investigations are made for voltage at the receiving end lagging the voltage at the sending end by 30° and 60°. The results are repeated for a higher value of the magnetising reactance of the series transformer. On account of the non-linearity introduced due to thyristor switching, harmonics are generated. Their magnitudes are calculated. A sample design procedure for a 5th harmonic filter is given. Impact of filter on the system resonances and thyristor currents is investigated to bring out the associated problems.

Experimental investigations of static phase-shifting concepts are carried out in the laboratory. Based on experimental results, the concept of generation of voltage across

the coil seemed to be a better design. The Thesis presents a preliminary study of a very important device - a thyristor controlled static phase-shifter and concludes that such a device is a practical idea which when implemented in power systems will provide a very valuable active power controller for both, regulating the power flow under steady state conditions and for stabilizing the system.

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LIST OF SYMBOLS

All the quantities below are p.u. values unless otherwise specified.

a, b, c,	Phase sequence
i	Instantaneous current of thyristor
i_L	Instantaneous line current
i_f	Instantaneous current of filter
I_{Ln}	Peak value of the nth harmonic component of line current
j	Complex operator($1\angle 90^\circ$)
n	Harmonic order
R_f	Resistance of the filter
R_L	Resistance of the line
V_A	RMS ac sending end voltage
v'_A	Modified phase voltage V_A
V_R	RMS ac receiving end voltage
v_A, v_{bc}, v_R	Instantaneous voltages
v_{valve}	Instantaneous voltage across the thyristors
V_{bc}	RMS ac supply voltage on the secondary of the main transformer (or exciting transformer)
v_T	Instantaneous voltage across the series transformer winding(or coil)

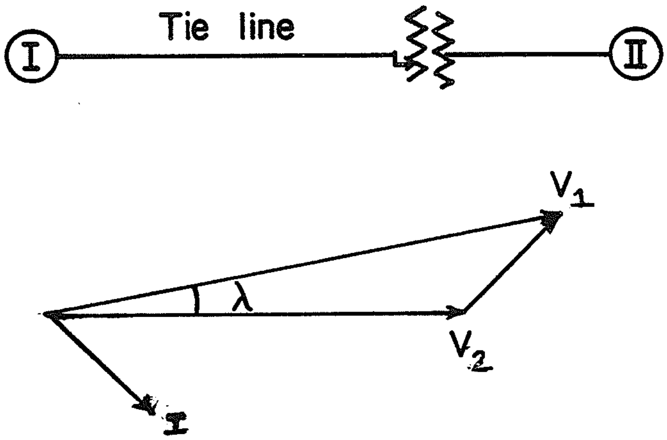
v_C	Instantaneous voltage across the capacitor
X_C	Capacitive reactance of the filter
X_f	Inductive reactance of the filter
X_{aL}	Internal impedance of the voltage sources v_A and v_R
X_T	Transmission line reactance
X_M	Magnetising reactance of the series transformer
X_L	Leakage reactance of the series transformer
α	Firing angle of thyristor in radians
λ	Phase-shift angle in radians
ϕ	Power factor angle
θ	Voltage angle
θ_R	Initial displacement between the two voltage sources V_A and V_R
ω	Angular speed in radians per second
t	Time, seconds
Δ	A small change in a variable
$\underline{V}$	Voltage phasor
$\underline{I}$	Current phasor

CHAPTER 1

INTRODUCTION

The demand for electrical energy is steadily increasing. To optimize energy resources, the power systems of the North American continent are interconnecting with neighbouring utilities causing more closed loops to be formed, and therefore, methods of power flow control are becoming increasingly important. It is a known fact that one of the serious problems encountered in the operation of interconnections is that of securing accurate and flexible means of regulating power flow[1]. This problem becomes more complex when the number of systems combined through interconnection into one group is increased. Intercompany contracts, tie-line capacity, and internal system limitations often require that the load exchanged at the various points be regulated within rather definite limits. Conditions have arisen where the maintenance of proper load division has been very difficult if not impossible. Although efforts are being made to broaden interchange contract requirements, it is sometimes difficult to avoid exceeding physical limitations and to secure the most efficient overall operation.

When two systems as shown in Fig. 1.1 are tied together at one point and are not connected to any other system,



PHASOR DIAGRAM

Fig. 1.1 Two Interconnected Systems.

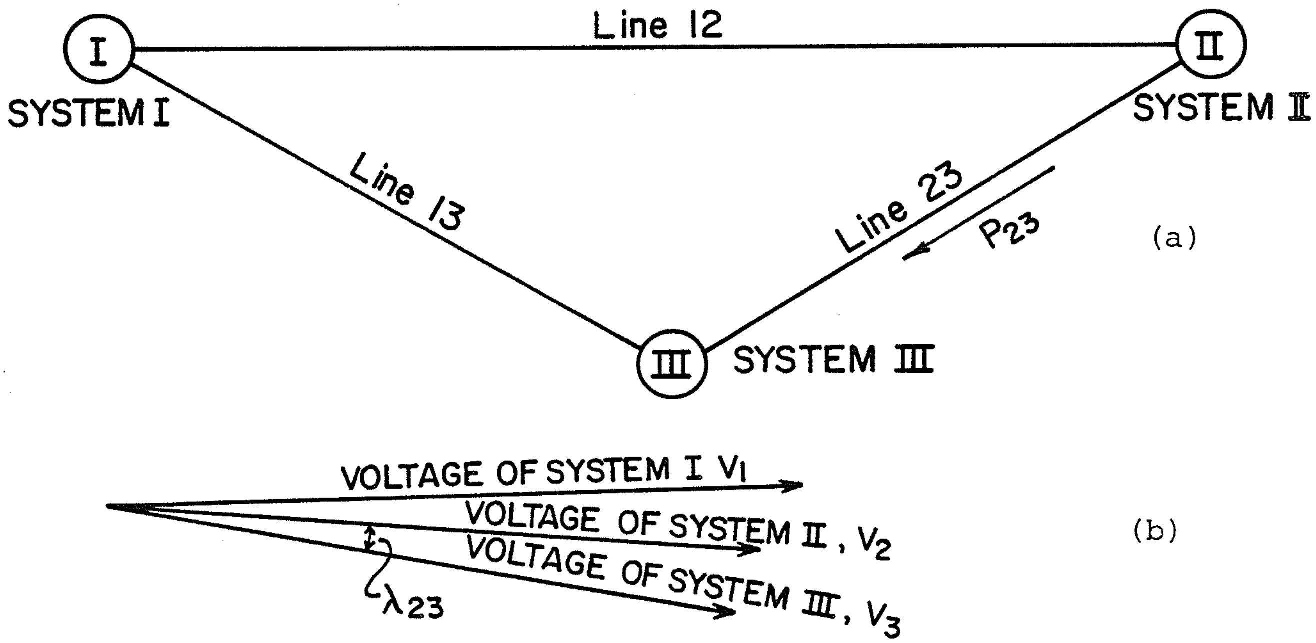


Fig. 1.2 (a) Interconnected Systems.
(b) Phasor Diagram for Line 23 Open.

the problem of active power control is simple. Should system 1 generate say 15 MW in excess of its own load, there is only one possibility, that 15 MW should go over the tie line to system II. If this power flow is to be maintained without frequency change, the increased generator output of system 1 must be carefully co-ordinated with a corresponding decreased output of prime movers by system II. The other chief problems are then to maintain adequate system stability and power factor control etc. If a system III is connected in turn to system II, the three not forming a closed loop, the problem of power control is very similar but somewhat more complex. Proper sharing of load can be secured through speed adjustments for any number of systems connected in series. But, the regulation becomes more and more difficult as the number of systems is increased.

If, however, the systems are interconnected to form a mesh, the problem of power control becomes entirely different which can not be corrected by governor adjustment. In other words, if the three systems (shown in Fig. 1.2) are connected to form a mesh, a shift of load on the tie between 1 and II would result in power flow in the other two tie lines.

The circulating kW in the closed loop, shown in Fig. 1.2, is produced from the phase lag produced on tie-line

12 by current flows, not being equal to the lag produced on line 13. When the loop is closed, the real power will start flowing over the tie line 23 between systems II and III towards the lagging phase angle as shown in Fig. 1.2.

Therefore $$P_{23} = \frac{|V_2|\,|V_3|}{|X_{L23}|} \sin \lambda_{23} \qquad (1.1)$$

The magnitude of the power that flows between system two and three, P_{23}, can be governed by the phase difference of the two systems (λ_{23}) and the impedance between them. This can not be controlled by voltage changes or generation excitation. If line 23 is opened, the phase angle, λ_{23}in Fig. 1.2 that appears across the breaker can be calculated from equation 1.1. This uncontrollable circulating power would naturally upset normal interchange even for system III not directly interested. This would also increase the load on several important lines and transformers possibly necessitating increased capacity at certain points and would result in overheating and damaging the lines[2].

In interconnections forming a closed mesh, circulating real and reactive power is generally produced due to unsymmetrical system setup and loading such as: difference in percent impedance of lines, unequal number of transformations, location of power plants near the end of the transmission system, and non-uniform loading . To eliminate the circulating kW flow, phase angle regulation is used.

1.1 Conventional On - Load Tap - Changing Phase-Shifter[1,3]

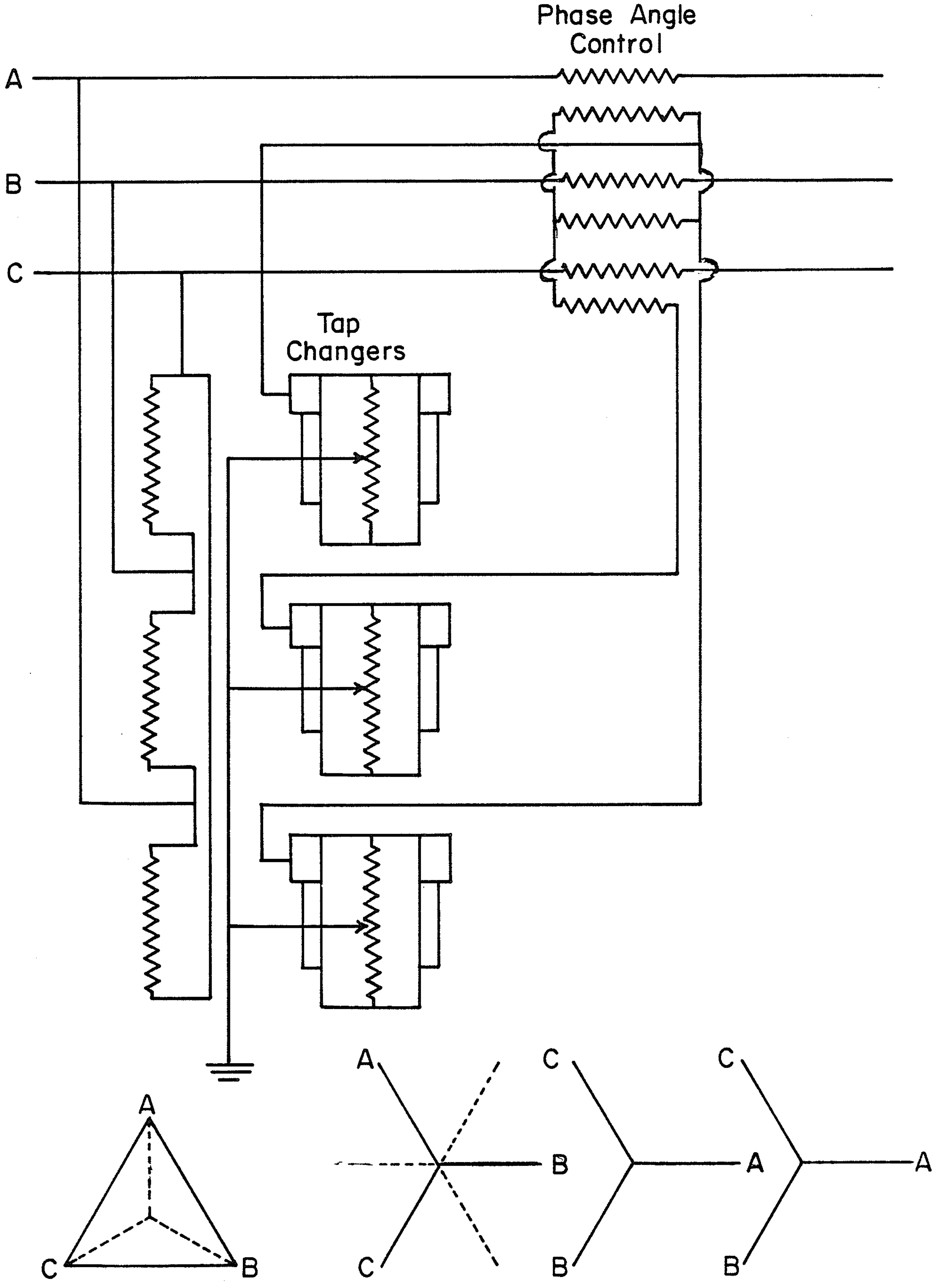
These phase-shifting transformers employ on-load tap-changers to provide a control on the phase-shift they introduce. The single line diagram of Fig. 1.3 illustrates the basic circuit of this device[3]. There are many disadvantages of the use of on-load tap - changing control, where the current is switched from tap to tap by mechanical means. The main disadvantages are its cost and the moving parts, the inertia of which reduce the speed of response producing temporary voltage variations and the high cost of maintenance required by the mechanical switching due to contacts and oil deterioration[4].

To overcome the above problems, a new principle of static phase-shifter is being suggested.

This thesis is devoted to investigate the possibility of designing a novel type of thyristor controlled static phase-shifter for application in power systems for active power control. This device promises to provide an attractive technical alternative to transformer tap-changer type phase-shifter. The former is discussed in detail in Chapter 2.

1.2 Advantages of a Static Phase-Shifter

Disadvantages of the conventional arrangement are the advantages of static arrangement. There are no mechanical



Exciting Transformer Series Transformer

Fig.1.3 Diagram of Equipment for Shifting Phase-Angle.

taps in this arrangement. So this phase - shifter is more reliable and faster. Also, a shift of 30^o can be obtained without reversing the series transformer connection as the load current is directly controlled by the thyristor firing angle. This is discussed in detail in Chapter 2.

1.3 Disadvantages

They suffer from high harmonic current generation under steady-state conditions and high current rating of thyristor valves under transient overvoltage conditions. In this arrangement, as the thyristors are fed from an ideal voltage source, there is no need to introduce filters on the input side. The filters will be used to filter the current harmonics from the circuit of the controlled system.

The major emphasis of this thesis is, thus, on the developement of a new type of phase-shifter and its novel applications.

Chapter 2 is devoted to the theoretical analysis of the static phase-shifter, wherein the analysis of the harmonics and the design of the filter have also been dealt.

Chapter 3 illustrates the experimental setup to test the concepts and to ensure that no major point is overlooked in the theoretical analysis.

The overall conclusions and major contributions achieved in this thesis are summarized in Chapter 4.

CHAPTER 2

THYRISTOR CONTROLLED STATIC PHASE - SHIFTER: A NOVEL DESIGN

2.1 Introduction

Rapidly increasing number of interconnections between power systems is making it possible to shift loads from one system to another in either direction to take advantage of the diversity of system loads. This is resulting in improvements in the quality of service and in economies due to savings in plant capacity[3].

These interconnections are presenting the problems of controlling the power flow in definite paths through networks, which involve phase-angle control. The purpose of this thesis is to describe the equipment used for this purpose and present a new thyristor controlled phase-shifting device which has a very promising future,

2.2 Phase-Angle Control

If two or more interconnected systems or parts of one system form a closed loop, as shown in Fig. 2.1, conditions arise which can not be corrected simply by voltage control and by governor adjustments. The closed power loop

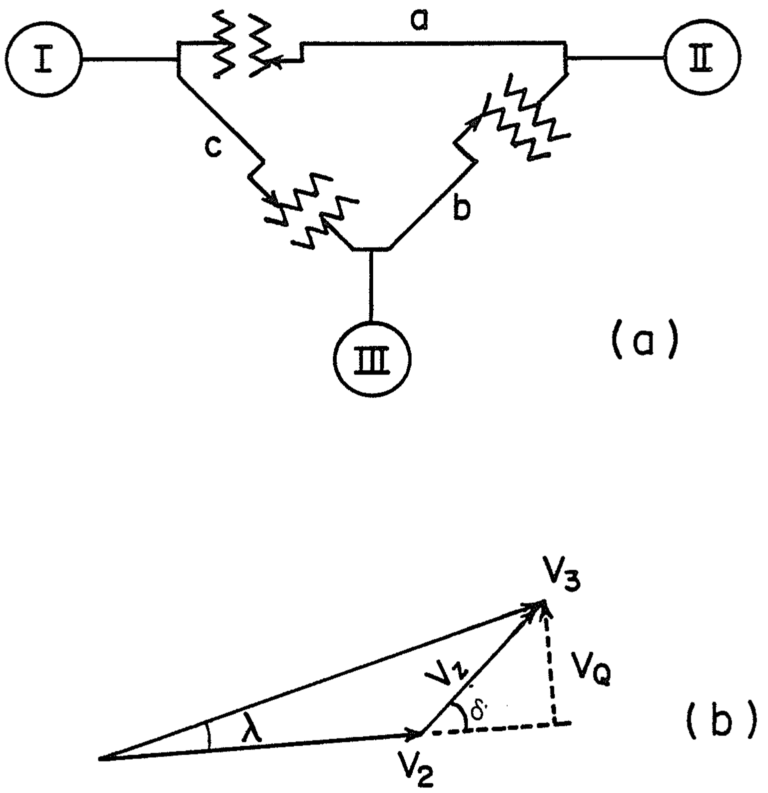


Fig. 2.1 (a) Three power systems interconnected to form a power loop.

(b) Phasor diagram showing the Conditions which exist when the line is opened.

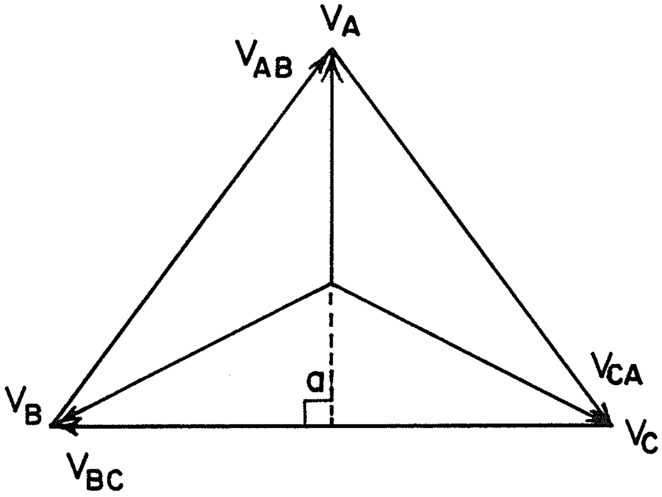


Fig. 2.2 Generation of a quadrature voltage component.

however, forms two paths between a generating station and the load at points around the loop. The tap-changing on-load voltage control equipment can be adjusted to obtain voltages of equal magnitude at a particular location in the power loop, but these voltages may not necessarily be in phase. For example, if the line is opened between stations II and III, Fig. 2.1 and voltages are measured; $V_3\angle\lambda$ on the station III side and $V_2\angle 0$ on station II side, there may be a voltage $V_Z\angle\delta$ between $\underline{V}_2$ and $\underline{V}_3$ across the open breakers. The dotted extension of $\underline{V}_2$ indicates how the voltages can be adjusted to equal magnitude by means of tap-changing on-load equipment for voltage control only, but a quadrature voltage V_Q still exists across the breaker, because V_2 and $V_3$are not in phase[3]. If the tie-line be connected to form a closed ring, current would flow from V_3, the line with leading voltage, to V_2 the line with lagging voltage.

If a voltage in quadrature with one of these delivered voltages, V_2 for example is added in the line to compensate for V_Q, the voltages V_2 and V_3 can be brought in to phase with each other. In order to prevent this circulating power which might upset exchange values, voltage conditions, and loading around the circuit, it would be necessary to introduce a quadrature voltage between V_2 and V_3 in the loop equal to the inherent displacement produced by circuit loading. It can be shown that for ordinary transmission circuits, the power flow is nearly proportional to the phase displacement of the voltage[1]. It is possible, therefore, to obtain accurate and flexible control of power exchange by supplying some equipment which will produce the required quadrature voltage in adjustable amounts and direction.

The simplest procedure to obtain a phase-shift in a voltage is to add to it a controlled component of phase quadrature voltage which can be generated from the other two phases. This procedure, works very well when the net phase-shift required is small, which usually is the case and, is easily implemented by phase-shifting transformers.

A phase quadrature voltage component is obtained in a three-phase system using transformers. The voltages from phases B and C of a three-phase system as shown in Fig. 2.2 are used to generate a voltage V_{BC} which is displaced by 90 degrees from the voltage of phase A. With suitable transformer connections a part of it can be added to the voltage of phase A. This implementation is shown in Fig. 1.3 of Chapter 1.

Developments in large power rating thyristors have led to new concepts which need a careful investigation. The research work described in this thesis is devoted to this end.

2.3 Replacement of On-Line Tap-Changers by Anti - Parallel Thyristor Switches.

The single line diagram of Fig. 2.3 illustrates the basic circuit of the above proposed solution, in which the inverse parallel connected thyristors operate as switches. However there seem to be enormous technical and economical problems in the integration of thyristor switching with the conventional on-load tap-changer principle. The major problem faced is the ratings of the devices, which have to withstand full fault current and surge voltage conditions; another main problem relates to the large number of thyristor switches and the firing angle control circuits required for them[4].

The alternative is a trivial innovation and too expensive and hence not persued further.

2.4 Use of Thyristors to Generate Controlled Phase - Quadrature Voltage Component

The use of thyristors to generate controlled phase-quadrature voltage component is a novel, unconventional concept and is very promising. Consider Fig. 2.4 where a

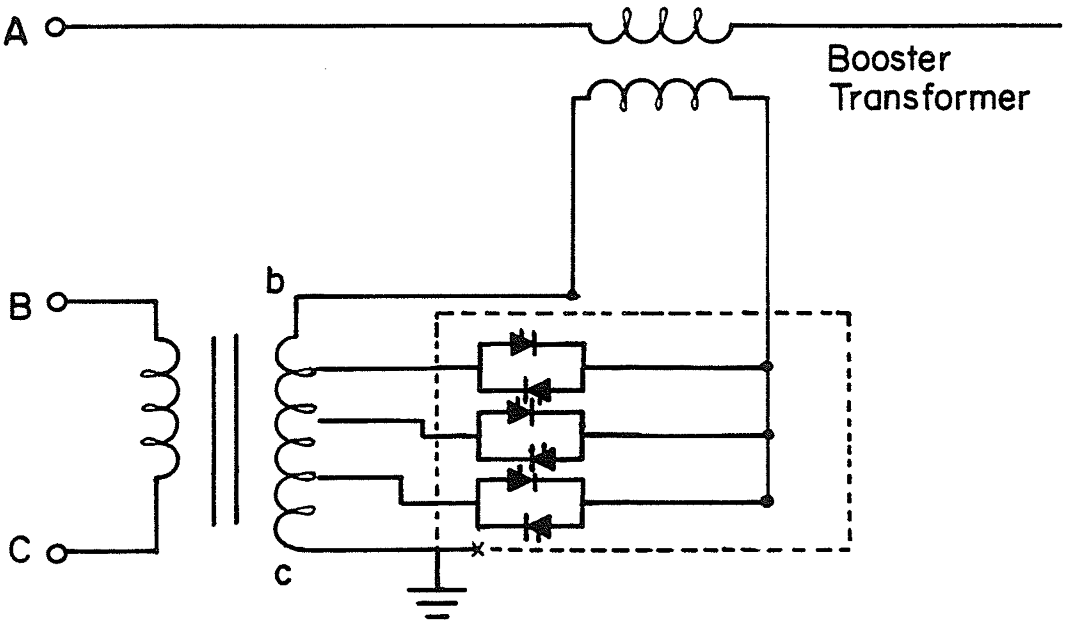


Fig. 2.3 Replacement of on-load tap-changer by anti-parallel thyristor switches.

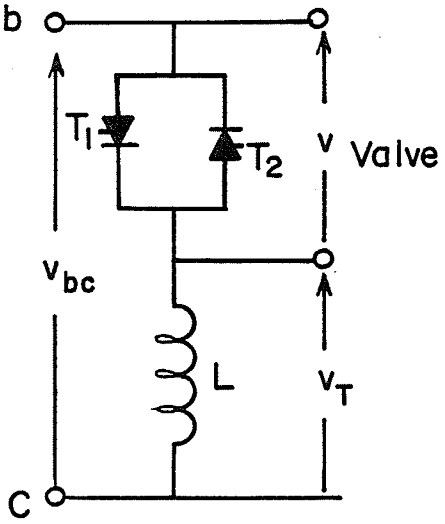


Fig. 2.4 Application of thyristor phase-control to generate a variable magnitude voltage component.

voltage v_{bc} is applied to an anti-parallel thyristor pair connected in series with a coil L. The controlled firing of thyristor pair results in voltages across the thyristor pair v_{valve} and coil v_T as shown in Fig. 2.5.

The voltage v_{bc} appears across the thyristors when they do not conduct and across the coil when they do. The voltages v_{valve} and v_T can be resolved into their fundamental and harmonic components. It is easy to understand that the harmonic components of both voltages v_{valve} and v_T are equal. The fundamental components of v_{valve} and v_T depend upon the firing angle α as will be illustrated later. This arrangement therefore provides a mechanism of obtaining a variable magnitude of voltage by a simple firing angle control of thyristors.

In order to make use of this technique for phase shifting controller one can use the voltage v_{valve} or v_T obtained from v_{bc} as shown in Figs. 2.6 and 2.7 to be added to v_A. In either case however there is a need for effective filtering of harmonics.

If v_T is to be used it is possible to use the transformer winding in place of a separate coil.

In this thesis both possibilities are researched.

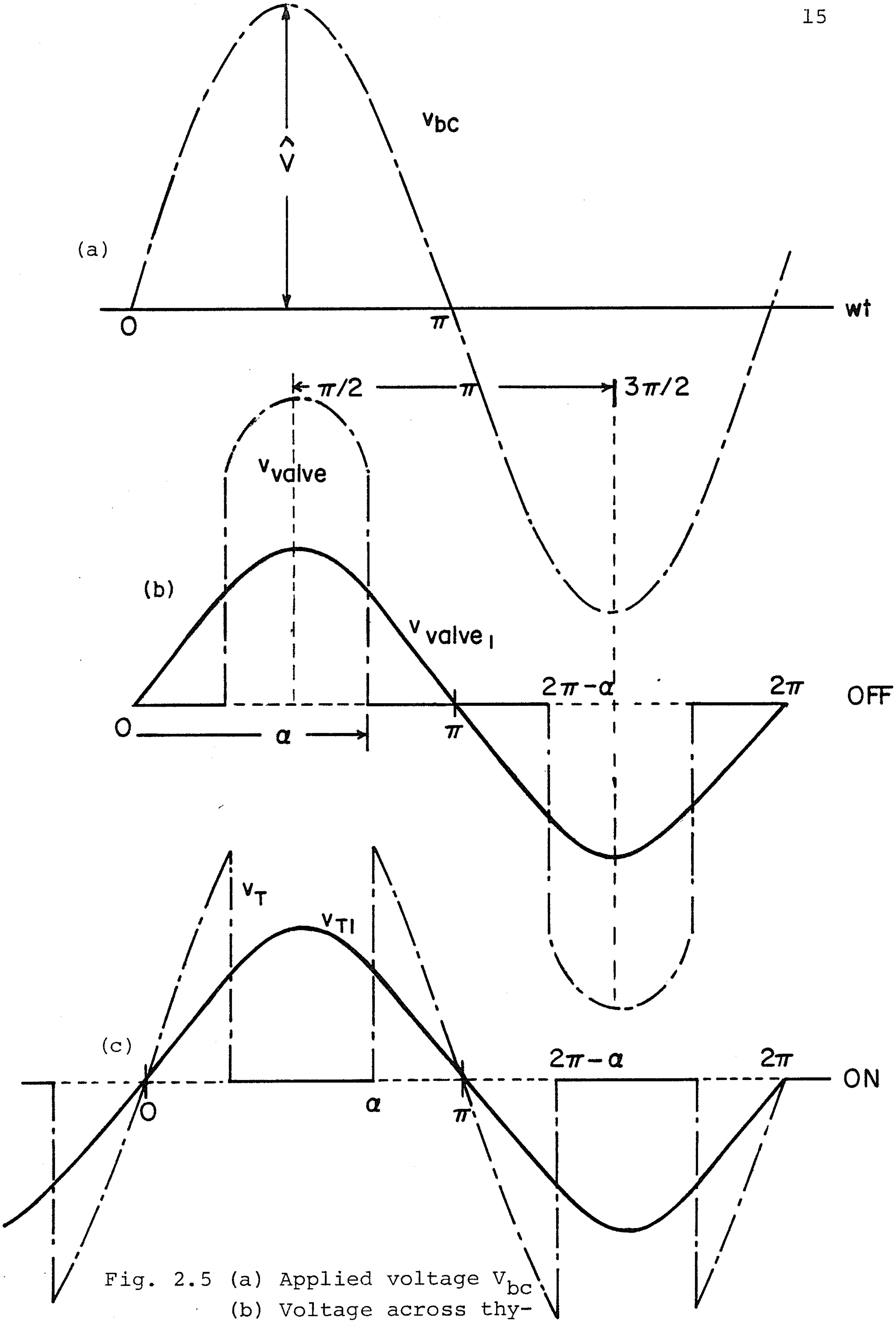


Fig. 2.5 (a) Applied voltage V_{bc}
(b) Voltage across thyristors.
(c) Voltage across coil.

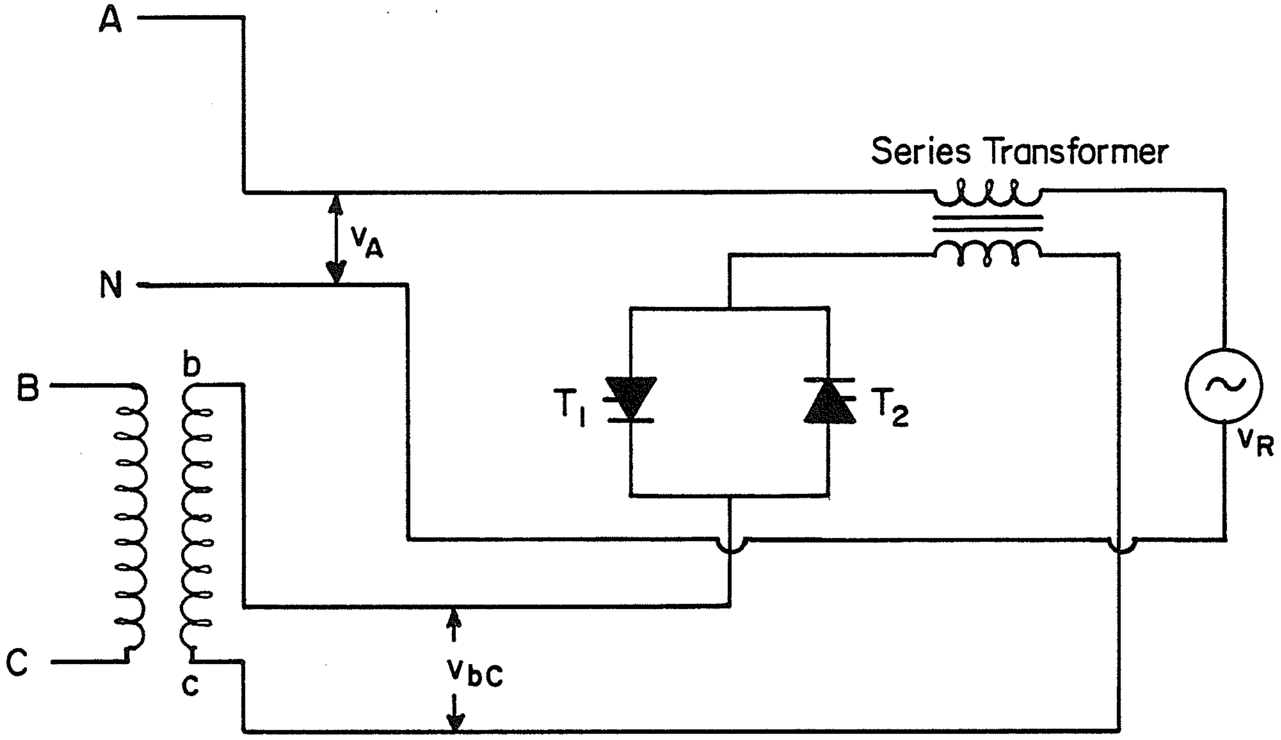


Fig. 2.6 Injection of voltage v_{bc} across the coil.

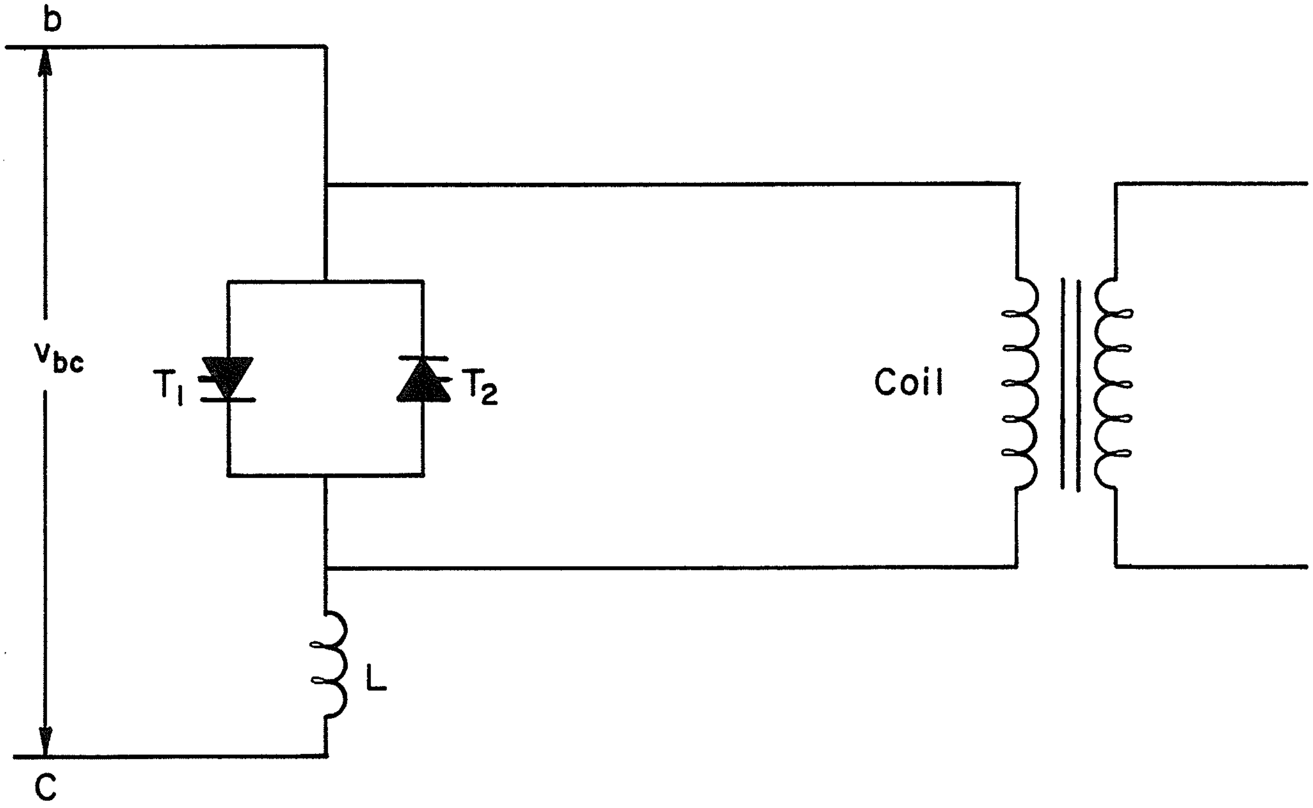


Fig. 2.7 Injection of voltage v_{bc} across the valve.

By exploiting the above mentioned concept, it is feasible to obtain accurate and flexible control of power exchange by supplying the required quadrature voltage in adjustable amounts and direction to the system.

2.5 Load and Phase-Angle Requirements

The range of phase-angle control required to attain the desired power flow is made up of two component parts.

(a) The natural phase-angle which may exist at any time due to load and generating conditions and the resulting net power flow in each individual sections of the entire loop.

(b) The quadrature voltage necessary to send the desired amount of power through the tie-line in the proper direction.

Fig. 2.6 shows a single-phase schematic diagram for one type of proposed static phase-shifter. A satisfactory control is obtained for $90 < \alpha < 180^{\circ}$.

The remaining part of this chapter is devoted to a systematic analysis of this configuration. Fig. 2.8 represents the equivalent circuit in which the impedance of all sources is lumped with the transmission line for theoretical investigations. Since the model in Fig. 2.8 is purely inductive it is possible to determine uniquely the conduction period of each thyristor for a given value of firing angle α.

Refer to Fig. 2.9, when the thyristors conduct, v_{bc} appears across the primary winding (or coil).

Then $v_{bc} = L.\frac{di}{dt}$:Instantaneous voltage

$$\text{or} \quad i = \frac{1}{L}\int_{\alpha}^{\theta} v_{bc}\, dt$$

$$\text{if} \quad v_{bc} = \hat{v} \sin(\omega t)$$

$$\text{Then} \quad i = \frac{1}{L}\int_{\alpha}^{\theta} \hat{v} \sin(\omega t) dt$$

$$= \frac{\hat{v}}{\omega L} \left(- \cos \theta + \cos \alpha \right) \qquad (2.1)$$

Since $i = 0$, at $\theta = \Psi$

From equation 2.1 $\Psi = 2\pi - \alpha$

So thyristor (1) will conduct from α to $2\pi - \alpha$

The second thyristor starts conducting at $\alpha + 180^{o}$

2.6 Fundamental Voltage and Phase-Angle

In order to study the characterstic performance of the device in the steady state, it is important to derive a direct relationship between its input parameter (control angle α) and its output quantity (Phase-Angle). Referring to the model in Fig. 2.8, v_{bc} represents a voltage component which is injected at one end of the transmission line, at the sending end to provide a phase-shift λ for controlling the power flow in the line. But v_{bc} is in quadrature with