



Investigations on a hybrid topology for static reactive power compensation
by Madhav D Manjrekar

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Electrical Engineering,
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Abstract:

Reactive power flow control has been recognized as a significant factor in the design and operation of ac electric power systems. The principal objective for controlling reactive power flow is the voltage regulation in a power distribution system. Reactive power compensation also improves the stability limits of power transfer in a transmission system. Present compensation techniques employ thyristor switched networks which are generally adequate enough to perform the desired control. However, the quality of their performance is constrained due to their harmonic interactions with the utility system. Number of topologies based on self commutated - devices have been studied as an alternative approach. This technique offers a harmonic free interface with the utility system, but it requires the power devices which can be scaled to high power ratings.

A synergistic approach which brings together the high power capability of thyristor controlled equipment and the harmonic free interface of the self commutated converters is presented in this thesis. The hybrid topology presented herein consists of a series combination of a thyristor controlled static VAr compensator and a power electronic reactive current injector. The evolution and the operating principles of this hybrid static reactive power compensator are discussed in the thesis. Design procedures and control strategies for the proposed hybrid reactive compensator are outlined. A formal stability analysis of a current controlled static VAr compensator investigating the dynamic performance of the hybrid compensator is included in this thesis.

The hybrid reactive compensator is modelled in MATLAB-Simulink software. The feasibility of this hybrid approach is demonstrated by results of simulations in the lagging and leading compensation zones. The simulation results also verify the stability analysis which predicts loss of a periodic steady state near the full capacity leading compensation operating point. A laboratory experiment is performed to verify the model used for the firing angle generator in the hybrid system. The results of the investigations, limitations of the proposed approach and suggestions for future studies are further elaborated in the concluding chapter of this thesis.

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by

Madhav D. Manjrekar

A thesis submitted in partial fulfillment
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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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TABLE OF CONTENTS

Chapter	Page
1. INTRODUCTION.....	1
Introduction.....	1
Organization of Thesis.....	4
2. REVIEW OF STATIC REACTIVE POWER COMPENSATORS.....	6
Introduction.....	6
Classification of Static Reactive Compensators.....	7
Variable Reactance Type Compensators.....	7
Mechanically Switched Compensator.....	8
Thyristor Controlled Reactor.....	10
Thyristor Switched Capacitor.....	11
Static VAr Compensator.....	13
Pulse Width Modulated Compensator.....	15
Variable Voltage Source Type Compensators.....	16
Hybrid Compensators.....	22
Comparison of Static Reactive Compensators.....	26
Summary.....	27
3. HYBRID STATIC REACTIVE POWER COMPENSATOR.....	29
Introduction.....	29
Evolution and Operation of the Hybrid Reactive Power Compensator.....	30
Selection of Reactive Elements.....	38
Constraints on the Reactive Current Injector.....	41
Control Strategies.....	42
Start-up and Scheduling Strategy.....	44

TABLE OF CONTENTS (Continued)

Chapter	Page
4. STABILITY ANALYSIS OF A CURRENT FED STATIC VAR COMPENSATOR.....	47
Introduction.....	47
Stability Analysis.....	48
5. MODEL OF THE HYBRID STATIC REACTIVE POWER COMPENSATOR.....	55
Introduction.....	55
Block Diagram Representation of the Hybrid Compensator.....	55
MATLAB-Simulink Model of the Hybrid Compensator.....	57
Model of the SVC.....	58
Model of the RCI and the CIT.....	60
Model of the FAG.....	61
6. SIMULATION AND EXPERIMENTAL RESULTS	65
Introduction.....	65
Start-up Characteristics.....	66
Dynamic Performance in the Lagging Compensation Zone.....	68
Steady State Performance in the Lagging Compensation Zone.....	71
Dynamic Performance in the Resonance Zone.....	75
Dynamic Performance in the Leading Compensation Zone.....	79
Steady State Performance in the Leading Compensation Zone.....	82
Performance Near Full Capacity Leading Compensation.....	85
Experimental Results.....	88
7. CONCLUSIONS.....	98
REFERENCES.....	101
APPENDIX	
Derivation of the Relation between the Firing Angle and the Total Reactance of a Current Fed Static VAr Compensator....	103

LIST OF TABLES

Table	Page
1. Qualitative comparison of static reactive compensators.....	26
2. Comparison of the experimental and calculation results.....	90

LIST OF FIGURES

Figure		Page
1.	Variable reactance type compensator.....	7
2.	Variable compensation by mechanical switching of reactive elements.....	8
3.	Various configurations of variable reactance type compensators.....	9
4.	Variable reactive compensation by TCR.....	10
5.	Typical TCR current and the source voltage waveforms.....	11
6.	Variable reactive compensation by TSC.....	12
7.	Typical TSC current and the source voltage waveforms.....	12
8.	Variable reactive compensation by SVC.....	13
9.	Typical capacitor voltage and TCR current waveforms.....	14
10.	Variable reactive compensation by PWM controlled reactance.....	15
11.	Variable voltage source type compensator.....	17
12.	Simplified schematic of a VSI.....	18
13.	Simplified schematic of a transformer coupled MLI.....	19
14.	Simplified schematic of a diode clamped MLI.....	20
15.	Simplified schematic of a H-bridge MLI.....	20
16.	Simplified schematic of a pulse width modulated three phase VSI.....	21
17.	Simplified schematic of a pulse width modulated three phase CSI.....	21
18.	Simplified schematic of a hybrid compensator with VSI and CSI.....	23
19.	Simplified schematic of a hybrid compensator with VSI and MLI.....	24
20.	Simplified schematic of a hybrid compensator with VSI and SVC.....	25
21.	Reactive compensation by a simple capacitor.....	30
22.	Voltage regulation by reactive current injection.....	31
23.	Variable reactive compensation by RCI.....	32
24.	Reactive compensation by a series connection of RCI and a variable impedance	33
25.	Simplified schematic of the hybrid static reactive power compensator.....	34
26.	Equivalent circuits of the hybrid reactive compensator.....	37
27.	Functional representation of SVC in the hybrid reactive compensator.....	38
28.	Plot of equivalent reactance of the current fed SVC v/s the firing angle.....	40
29.	Simplified block schematic of the proposed control system.....	43
30.	Precharging mode of the SVC capacitor at the start-up.....	45
31.	Start-up and scheduling strategy.....	46
32.	Simplified schematic of the hybrid reactive compensator.....	48
33.	Simplified schematic of a current fed SVC.....	49

LIST OF FIGURES (Continued)

Figure	Page
34. Typical capacitor voltage and TCR current waveforms.....	50
35. Block schematic illustrating power circuit interconnections of the hybrid reactive compensator.....	56
36. Simplified block schematic of the hybrid reactive compensator system.....	57
37. Block schematic illustrating the subsystems of the hybrid compensator model.....	57
38. Model of the capacitor used in the SVC.....	58
39. Model of the TCR used in the SVC.....	59
40. Model to simulate the start-up precharging algorithm.....	61
41. Model to simulate the lookup table enabling algorithm.....	63
42. SVC capacitor voltage during the precharging interval.....	67
43. SVC capacitor current during the precharging interval.....	67
44. Transient in the reactive current command in the lagging compensation zone.....	68
45. Transient in the reactive current in the lagging compensation zone.....	69
46. Transient in the firing angle in the lagging compensation zone.....	69
47. Transient in the TCR current in the lagging compensation zone.....	70
48. Transient in the SVC voltage in the lagging compensation zone.....	71
49. Steady state reactive current command in the lagging compensation zone.....	72
50. Steady state reactive current in the lagging compensation zone.....	72
51. Steady state the firing angle in the lagging compensation zone.....	73
52. Steady state TCR current in the lagging compensation zone.....	73
53. Steady state SVC voltage in the lagging compensation zone.....	74
54. Transient in the reactive current command in the resonance zone.....	75
55. Transient in the reactive current in the resonance zone.....	76
56. Transient in the firing angle in the resonance zone.....	76
57. Transient in the TCR current in the resonance zone.....	77
58. Transient in the SVC voltage in the resonance zone.....	78
59. Transient in the reactive current command in the leading compensation zone.....	79
60. Transient in the reactive current in the leading compensation zone.....	80
61. Transient in the firing angle in the leading compensation zone.....	80
62. Transient in the TCR current in the leading compensation zone.....	81
63. Transient in the SVC voltage in the leading compensation zone.....	81
64. Steady state reactive current command in the leading compensation zone.....	82
65. Steady state reactive current in the leading compensation zone.....	83
66. Steady state firing angle in the leading compensation zone.....	83

LIST OF FIGURES (Continued)

Chapter	Page
67. Steady state TCR current in the leading compensation zone.....	84
68. Steady state SVC voltage in the leading compensation zone.....	84
69. Reactive current command near full capacity leading compensation point.....	85
70. Reactive current near full capacity leading compensation point.....	86
71. Firing angle near full capacity leading compensation point.....	86
72. TCR current near full capacity leading compensation point.....	87
73. SVC voltage near full capacity leading compensation point.....	88
74. Circuit schematic of the experimental set-up.....	89
75. Comparison of the experimental and calculation results for the reactance of the current fed SVC.....	91
76. Line voltage and line current in the full capacity leading compensation mode.....	92
77. SVC voltage and TCR current in the full capacity leading compensation mode.....	93
78. Line voltage and line current in the full capacity lagging compensation mode.....	94
79. SVC voltage and TCR current in the full capacity lagging compensation mode.....	95
80. Line voltage and line current in the resonance mode.....	96
81. SVC voltage and TCR current in the resonance mode.....	97
82. Simplified schematic of a current fed SVC.....	103
83. Typical voltage and current waveforms for the current fed SVC for one current cycle.....	104

ABSTRACT

Reactive power flow control has been recognized as a significant factor in the design and operation of ac electric power systems. The principal objective for controlling reactive power flow is the voltage regulation in a power distribution system. Reactive power compensation also improves the stability limits of power transfer in a transmission system. Present compensation techniques employ thyristor switched networks which are generally adequate enough to perform the desired control. However, the quality of their performance is constrained due to their harmonic interactions with the utility system. Number of topologies based on self commutated devices have been studied as an alternative approach. This technique offers a harmonic free interface with the utility system, but it requires the power devices which can be scaled to high power ratings.

A synergistic approach which brings together the high power capability of thyristor controlled equipment and the harmonic free interface of the self commutated converters is presented in this thesis. The hybrid topology presented herein consists of a series combination of a thyristor controlled static VAR compensator and a power electronic reactive current injector. The evolution and the operating principles of this hybrid static reactive power compensator are discussed in the thesis. Design procedures and control strategies for the proposed hybrid reactive compensator are outlined. A formal stability analysis of a current controlled static VAR compensator investigating the dynamic performance of the hybrid compensator is included in this thesis.

The hybrid reactive compensator is modelled in MATLAB-Simulink software. The feasibility of this hybrid approach is demonstrated by results of simulations in the lagging and leading compensation zones. The simulation results also verify the stability analysis which predicts loss of a periodic steady state near the full capacity leading compensation operating point. A laboratory experiment is performed to verify the model used for the firing angle generator in the hybrid system. The results of the investigations, limitations of the proposed approach and suggestions for future studies are further elaborated in the concluding chapter of this thesis.

CHAPTER 1

INTRODUCTION

Introduction

Reactive power flow has been recognized as a significant factor in the design and operation of ac electric power systems [1-3]. Generally, it has been observed that, the transmission of active power depends upon the angular phase difference between the voltages at the sending and receiving points of a power distribution line. The reactive power exchange, on the other hand, is dependent upon the relative magnitude of the voltages.

The most significant and the foremost objective for controlling reactive power flow is the voltage regulation in a power distribution system [1]. Almost all loads demand variable reactive power which causes variation in the voltage at the supply point. Moreover, reactive power is also consumed in the utility network elements (which are predominantly reactive) which exacerbates the problem. Power system designers and operators strive to maintain the voltage at various load locations within defined limits [2]. One solution to the problem of varying reactive power demand would be to provide independent voltage generation at all load buses. But this would be uneconomical in practical situations [1]. A more practical approach would be to have the generation

according to the real power requirement and manage the reactive power demand exclusively by means of compensators at the key nodes in the utility lines [4].

Secondly, the transient stability of the generating machine and the utility line system depends upon the machine dynamics and the amount of real power exchange [1]. Certain types of compensation techniques like mid-point compensation [4] improve the stability limits of power transfer and thus ensure safer operation at same level of power transfer or enable more power transfer with the same level of security.

A reactive power compensator acts as a controlled source of reactive power, as a voltage regulating feedback device, and as a network of desired susceptances. Ideally, it is expected to perform the following functions;

- i. to help produce a substantially flat voltage profile at all levels of power demand;
- ii. to improve stability by increasing the maximum transmissible power;
- iii. to provide an economical means for meeting the reactive power requirements of a utility system;

The reactive power demand being load dependent, the compensator is required to deliver variable reactive power. An overexcited synchronous machine or a synchronous condenser has been one of the methods of choice to provide reactive compensation in the past [1]. More recently, with the development of the semiconductor switches, static methods of reactive compensation can be obtained by connecting a variable reactance

network in shunt on the utility line. Reactive compensation can also be accomplished by connecting a variable ac voltage source with a series inductance to a utility line.

Numerous topologies have been presented [1,5] in either category. Present static reactive power compensators used for power flow control are based on thyristor switches. They are generally adequate enough to perform the required fundamental reactive power flow control. However, they have been identified to be bulky, as well as to suffer from harmonic interactions with the system [6]. Hence they require careful and custom design to operate reliably and efficiently. The interactions of the harmonics with the power systems have not been completely understood, and at times may result in instabilities [7]. On the other hand, the advanced self commutated power converters using gate turn-off devices have been proposed to overcome some of these disadvantages. These topologies require simple design as well as offer better level of performance [5,8]. The feasibility of this approach is being demonstrated in the field under number of pilot projects [4]. But even with potential advances in the power semiconductor technology, this approach is unlikely to reach the power levels possible with conventional thyristor switched equipment [9].

A hybrid approach that combines the two to achieve each of their best features (high power level and an interface free of harmonic interaction) simultaneously was presented recently [10,11]. The objective of this thesis is to investigate the properties of this hybrid approach to bring together the high power capability of thyristor controlled converters and the harmonic free interface of the self commutated converters.

Organization of Thesis

The following chapter in this thesis provides a review of various techniques employed for static reactive power compensation. Reactive power compensators are broadly classified into the following three types :

- i. Variable reactance compensators;
- ii. Variable voltage source compensators;
- iii. Hybrid compensators;

These compensators are categorized on the basis of their topologies and a comparative evaluation is presented in Chapter 2.

Chapter 3 introduces the proposed hybrid compensator and describes its operation. Guidelines for selection and design of various circuit components are presented. The control scheme and the start-up strategy are also discussed elaborately in this chapter.

Chapter 4 presents the stability analysis of a current controlled Static VAR Compensator (SVC). The analysis is done for a single phase SVC model. The probable stable and unstable zones for this system are identified in this chapter.

Chapter 5 outlines the modelling aspects of the proposed compensator. The compensator is modelled in MATLAB-Simulink software. The features of the proposed hybrid compensator are discussed with the help of various block schematics and simulation models.

The simulation results confirming the operation of the hybrid approach are presented in Chapter 6. They verify the successful application of the proposed control scheme and the results of the stability analysis. The control scheme results are also supported by a performance evaluation of a laboratory model.

The final chapter includes an overview of the thesis with some remarks on the practical issues concerned with the operation of the proposed compensator. The thesis concludes with a discussion on the scope for further research on the topic.

CHAPTER 2

REVIEW OF STATIC REACTIVE POWER COMPENSATORS

Introduction

A reactive power compensator may be defined as a device which provides a controllable and variable amount of reactive power according to the requirements of the load. It helps to maintain the constant voltage characteristics at the load location in the steady state and ensure stability of the utility network under transient conditions [2]. Ideally, a compensator is expected to have the capability of continuous adjustment of the reactive power, with no response delay, and over an unlimited range (both in lagging and leading modes) [1]. There are number of approaches reported in the literature which perform the task of supplying variable reactive power [1,5].

This chapter presents an overview of some of these static reactive power compensation techniques. These type of compensators are based on solid state devices and unlike synchronous condensers, they have no rotating parts [1]. The following sections in this chapter present the classification and comparative evaluation of various static compensator topologies which can supply variable reactive power.

Classification of Static Reactive Compensators

As defined in the introduction, reactive power compensator is a device which can provide the required variable reactive power to the load and the utility network. The reactive compensation can be obtained by connecting a variable reactance in shunt on the utility line. It can also be accomplished by connecting a variable ac voltage source with a series inductance to the utility line. The following two subsections describe various devices which fall in these categories. The final subsection presents some approaches which have resulted from combining some of these topologies.

Variable Reactance Type Compensators

Variable reactive compensation can be provided by introducing a variable reactance (X) in shunt on the utility line [1] as shown in Figure 1.

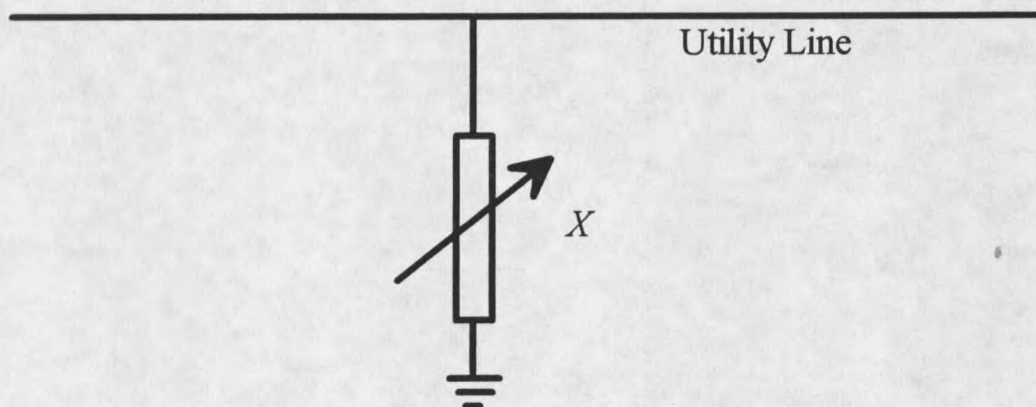


Figure 1. Variable reactance type compensator.

Mechanically Switched Compensator. The reactance X can be realized using capacitors or inductors which can exchange reactive power with the utility line (Figure 2). To provide variable compensation, the combination of different banks of these elements may be switched mechanically [1].

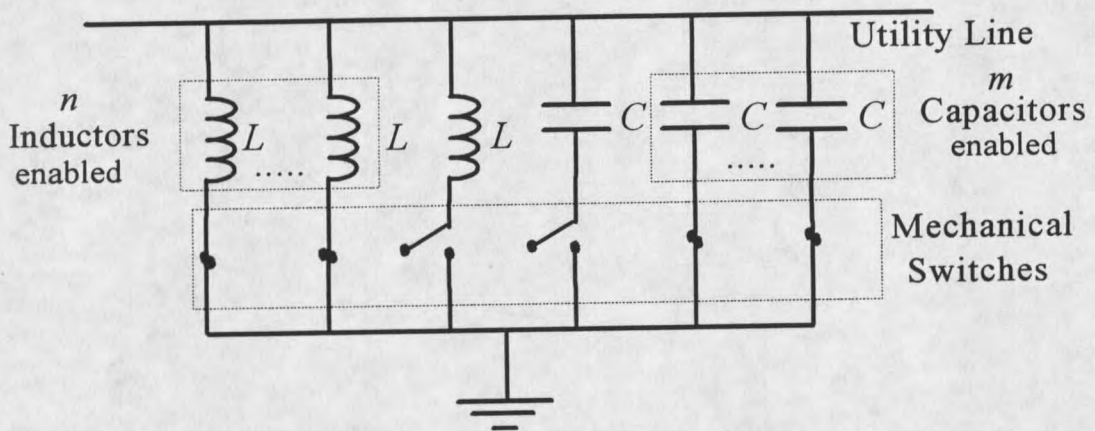


Figure 2. Variable compensation by mechanical switching of reactive elements.

As illustrated in the Figure 2, the switches connecting n inductors and m capacitors are closed. Under this condition, the equivalent reactance is given as

$$X = \frac{j\omega L}{n} \parallel \frac{1}{jm\omega C} \quad (2.1)$$

where ω is the supply frequency;

With recent advances in semiconductor technology, the mechanical switches have been replaced by semiconductor switches like thyristors. A variety of variable reactance networks such as Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor

(TSC) and their combinations like Static VAR Compensator (SVC) etc. have been discussed in reference [4]. Figure 3 shows different configurations of these reactive elements with the thyristor switches such as TCR, TSC, SVC and TCR parallel with TSC.

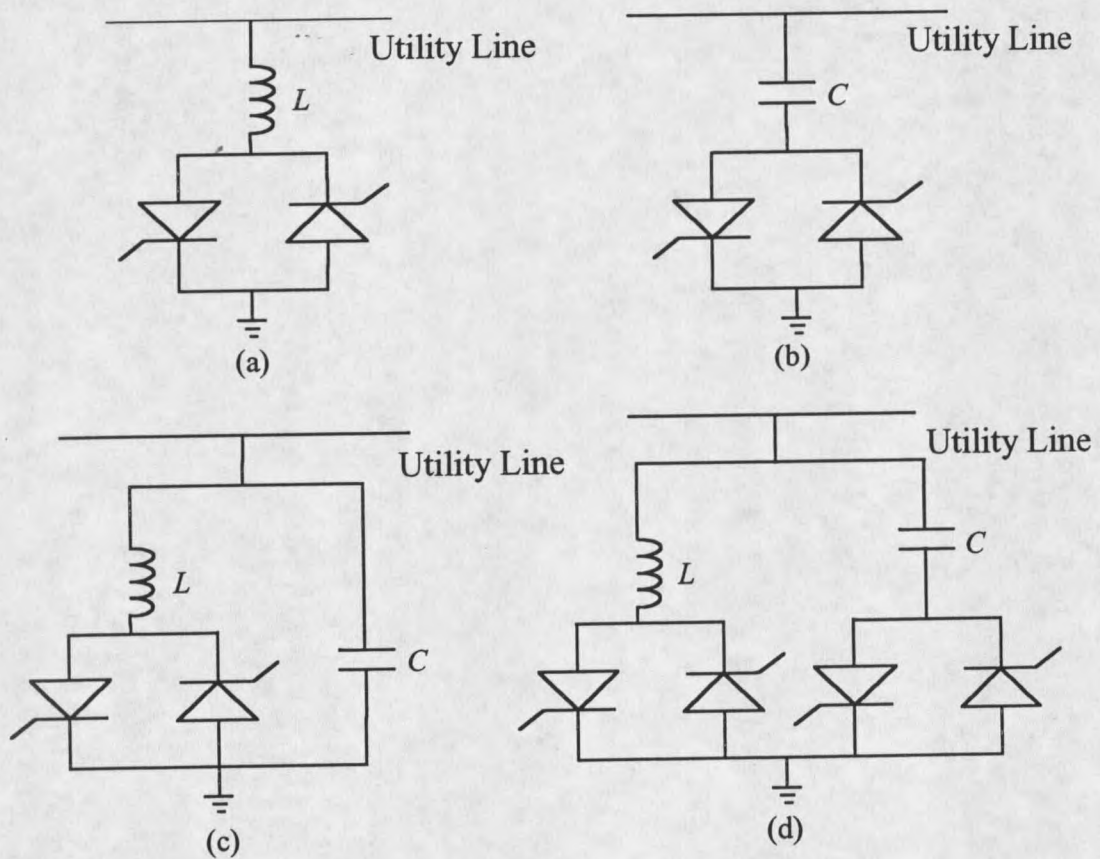


Figure 3. Various configurations of variable reactance type compensators :

- (a) Thyristor Controlled Reactor (TCR)
- (b) Thyristor Switched Capacitor (TSC)
- (c) Static VAR Compensator (SVC)
- (d) TCR parallel with TSC

The switching element of the variable reactance type compensators consists of two thyristors connected antiparallel, each conducting in alternate half cycles. They are turned on by supplying the firing pulses at their respective gates. The thyristors turn off when the current through them reaches zero. This is termed as natural commutation or line commutation. As shown in Figure 3, there are number of possible configurations of thyristor switched networks, the popular ones being TCR, TSC and SVC.

Thyristor Controlled Reactor (TCR). In TCRs the thyristors are turned on periodically in alternate half cycles and hence the inductor is included in the circuit for a fraction of a voltage cycle. Thus the equivalent inductance changes with the conduction time of the thyristors. For the system as shown in Figure 4, the typical TCR current waveform is illustrated in Figure 5.

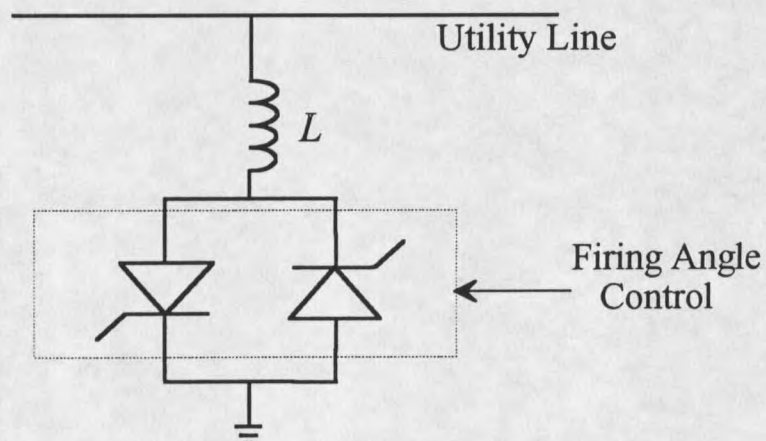


Figure 4. Variable reactive compensation by TCR.

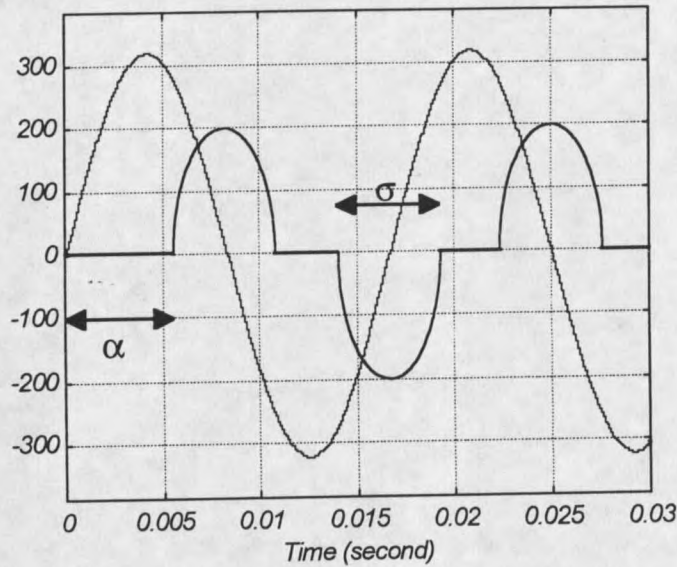


Figure 5. Typical TCR current (thick trace) and the source voltage (thin trace) waveforms. The firing angle (α) is equal to 120° .

As may be observed from Figure 5, the conduction angle (σ) of the thyristors varies with the firing angle (α). Thus the TCR current and consequently, the compensation level can be varied by changing the firing angle of the thyristors. The equivalent reactance of the TCR system in terms of the conduction angle (σ) is given by reference [6] as

$$X = j\omega L \frac{\pi}{\sigma - \sin \sigma} \quad (2.2)$$

where ω is the supply frequency;

Thyristor Switched Capacitor (TSC). In TSCs the thyristors act only as pure switches and are conducting for integral number of cycles unlike the TCRs. Thus for a

particular cycle, they either connect the capacitor on the utility line or disconnect it. By connecting multiple TSCs in parallel, the compensation level can be changed by varying the number of capacitors connected on the utility line as shown in Figure 6. Hence, the capacitive (leading) compensation can be varied only in discrete steps with TSCs.

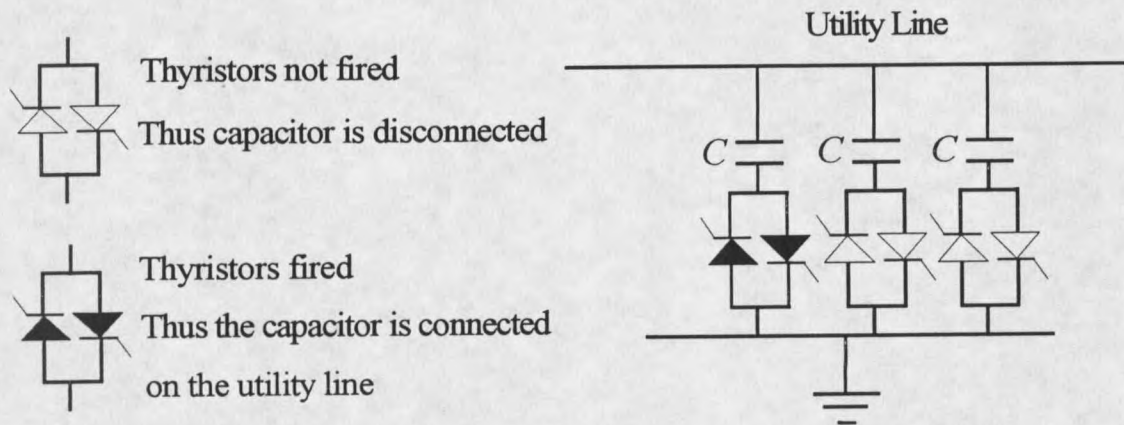


Figure 6. Variable reactive compensation by TSC.

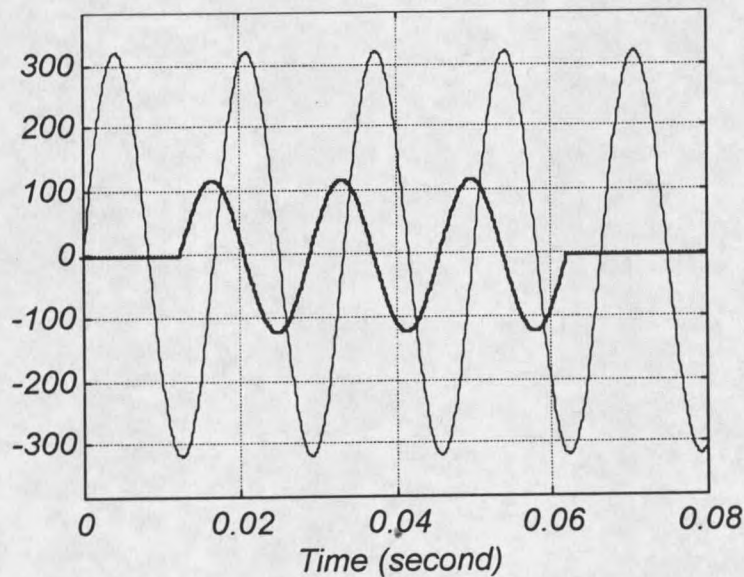


Figure 7. Typical TSC current (thick trace) and the source voltage (thin trace) waveforms.

The equivalent reactance when n capacitors are connected to the utility line is given by

$$X = \frac{1}{jn\omega C} \quad (2.3)$$

where ω is the supply frequency

As may be noticed from Figure 7, the TSC currents can be controlled only in integral number of cycles. Hence TSC offers a coarse and discrete control on compensation level, unlike the TCR which can provide finer compensation control. In order to achieve both, coarse and fine control on compensation levels, TCR and TSC may be used together in parallel as illustrated in Figure 3(d).

Static VAr Compensator (SVC). SVC is the most commonly used configuration amongst all of these types of variable reactance type compensators. It is a combination of a TCR and a fixed capacitor connected in parallel as illustrated in Figure 8.

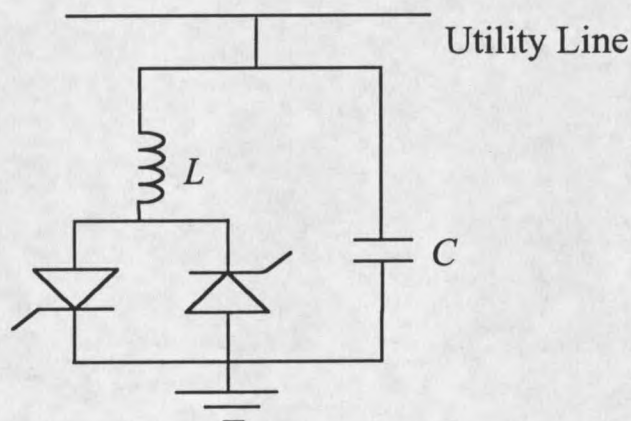


Figure 8. Variable reactive compensation by SVC.

As it includes both, capacitor and inductor, the SVC is capable of providing lagging as well as leading compensation. The typical capacitor voltage and TCR current waveforms in a SVC are illustrated in Figure 9.

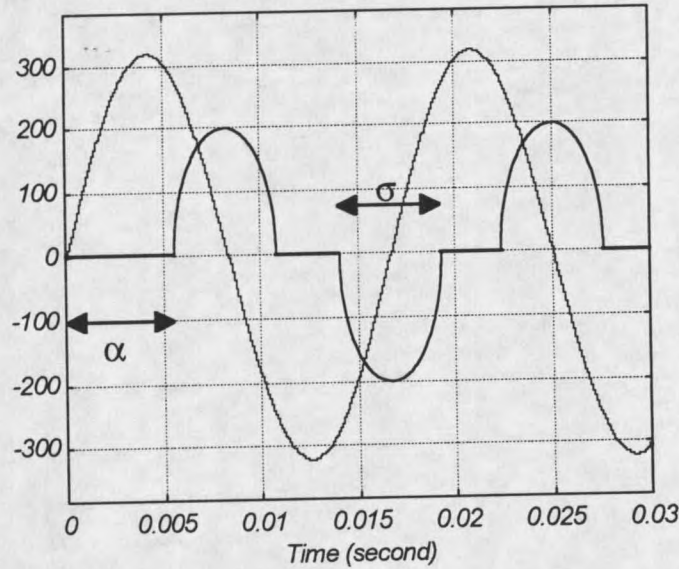


Figure 9. Typical capacitor voltage (thin trace) and TCR current (thick trace) waveforms. The firing angle (α) is equal to 120° .

As may be observed from this figure, the TCR is conducting only for a fraction of a period of the cycle called the conduction angle (σ) and the current drawn from the utility line is rich in low frequency harmonic content. Moreover, since the thyristors can be fired only in alternate half cycles, the response speed of the compensation is limited by this inherent time delay in thyristor gating control [1].

The equivalent reactance of the SVC system with inductor L and capacitor C is given by expression (2.4) :

$$X = \frac{j\omega L\pi}{\sigma - \sin \sigma} \parallel \frac{1}{j\omega C} \quad (2.4)$$

where ω is the supply frequency and σ is the conduction angle;

Pulse Width Modulated Compensator. To overcome the problems of large low order harmonics and slow response associated with the thyristor switching in a conventional SVC, Pulse Width Modulation (PWM) has been proposed [12] to control the reactance. A simplified schematic of this type of compensator is shown in Figure 10.

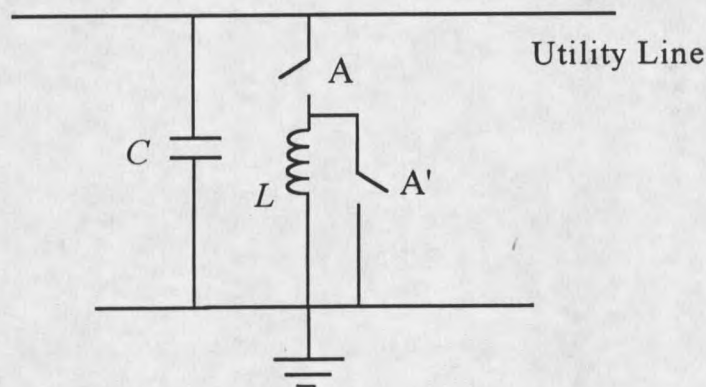


Figure 10. Variable reactive compensation by PWM controlled reactance.

The switches A and A' are two bi-directional gate turn-off type switches which can be closed and opened by gate control. Such power electronic switches which can be opened irrespective of the current through them or the voltage across them are also termed as forced commutated or self commutated devices. The gating signals for these devices are complementary in the sense when the switch A is on, A' is off and vice versa. Switch A' is used to freewheel the inductor current when A is turned off. The fundamental

component of the inductor current can be controlled through high frequency switching, and the total reactance can be expressed in terms of the switching duty ratio as given by expression (2.5).

$$X = \frac{j\omega L}{D^2} \parallel \frac{1}{j\omega C} \quad (2.5)$$

where ω is the supply frequency and D is the duty ratio of switch A;

Thus the reactive power can be adjusted continuously through the duty cycle control in this approach. This type of compensator does not generate low order harmonics. The high frequency harmonics which are of the order of the switching frequency can be attenuated using filters with small reactive elements. In the case illustrated in Figure 10, the filtering action is inherent due to the shunt capacitor. But this topology requires the forced commutated bi-directional switches which can withstand the voltages of the order of a typical utility line.

Variable Voltage Source Type Compensators

The reactive power exchange can also be varied by connecting a variable ac voltage source (V_s) in series with an inductor (X_L) to the utility line as shown in Figure 11 [4]. The reactive power exchange is controlled by varying the magnitude of the ac voltage (V_s). If the magnitude of the voltage source is greater than that of the utility line, the compensator provides leading compensation, and if it is smaller, it provides lagging compensation expressed by the following relationship :

$$I = \frac{V_L - V_s}{X_L} \quad (2.6)$$

where V_L is the utility line voltage;

V_s is the voltage synthesized by the voltage source;

I is the current injected in the utility system;

and X_L is the series reactance;

As is evident, when the synthesized voltage (V_s) is greater than the line voltage (V_L) the current polarity is positive denoting leading compensation. On the other hand, when the synthesized voltage is smaller, then the current polarity is negative signifying that it is lagging compensation.

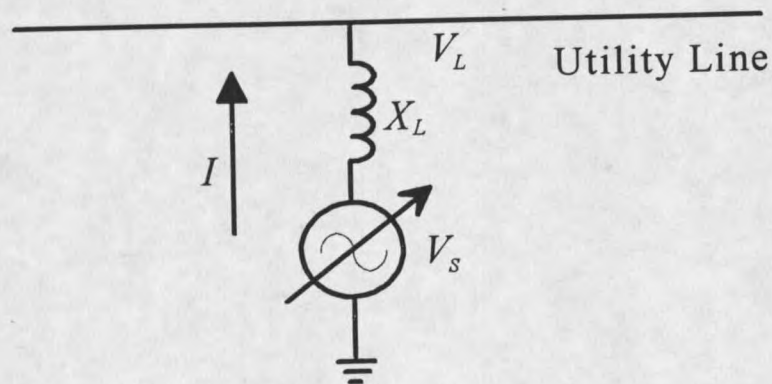


Figure 11. Variable voltage source type compensator.

The voltage source can be synthesized by a simple Voltage Source Inverter (VSI) as shown in Figure 12. By appropriate switching, the dc bus voltage is converted into bipolar ac voltage. The compensation level can be varied either by using a variable dc

source as shown in the figure or by using a tap changing transformer for connecting the source to the utility line. The leakage inductance of the transformer also acts as the coupling reactance (X_L).

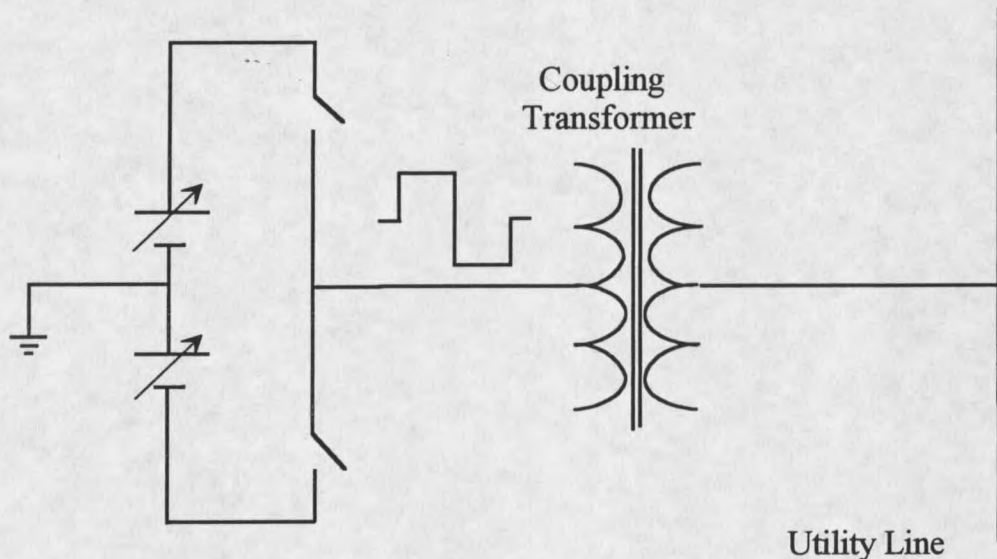


Figure 12. Simplified schematic of a VSI.

The output waveform of this type of converter is a simple square wave which is rich in harmonic content. To overcome this problem associated with a two level inverter, reference [13] proposes the use of multiple devices and thus employ Multilevel Inverters (MLI) instead of the usual two level types in order to generate a stepped waveform. These inverters can be used for reactive compensation applications through multilevel converter configurations in high power systems [14]. The multilevel switching is achieved through phase shifting of multiple two level converter output voltage waveforms which are added together vectorially using series connected transformer windings (Figure 13). However,

when the number of levels increases beyond three or five the approach becomes complex in realization due to the requirement of multiple transformer windings.

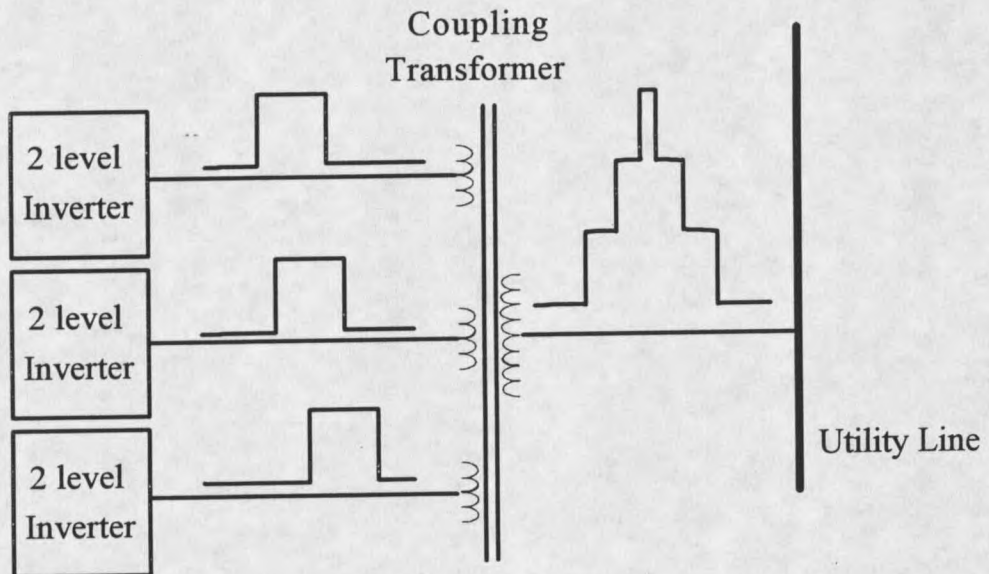


Figure 13. Simplified schematic of a transformer coupled MLI.

As an alternate approach, multilevel waveforms may be synthesized without the use of complex multiwinding transformers using a multiple dc bus inverter [15,16]. Representative topology of these inverters is illustrated in Figure 14. Reference [17] provides an excellent overview of the operation and characteristics of these topologies for reactive compensation applications.

[13] presents an alternative topology for multilevel conversion. Figure 15 illustrates one phase of the schematic of the power circuit of a five level inverter using this

approach. The advantage of this topology is that it provides flexibility for expansion of the number of levels easily without introducing undue complexity in the power circuit.

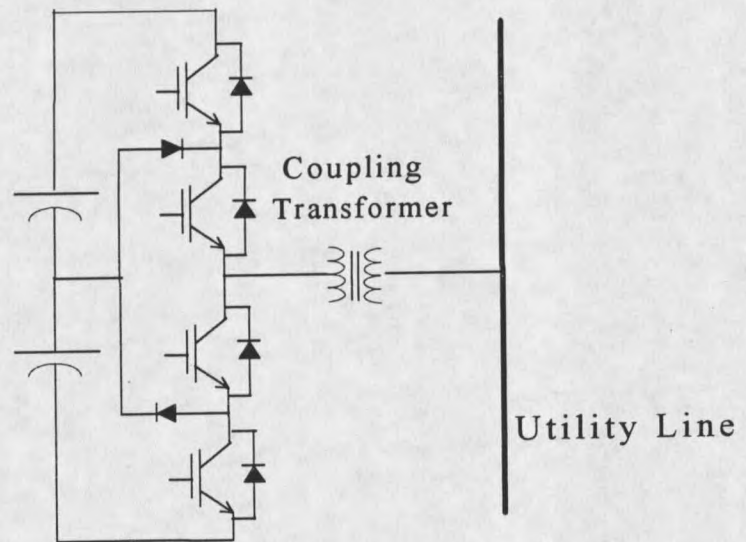


Figure 14. Simplified schematic of a diode clamped MLI.

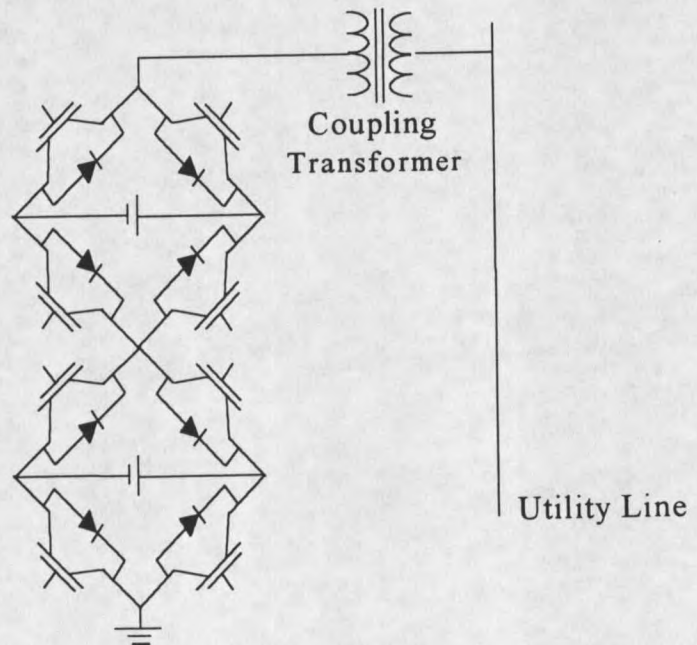


Figure 15. Simplified schematic of a H-bridge MLI.

Another alternative method to decrease harmonic distortion in two level inverters is the use of Pulse Width Modulation (PWM). Such strategies have been proposed for reactive power compensation applications in literature for Voltage and Current Source Inverters (VSI and CSI) [18]. Simplified schematics of these inverters for three phase applications are illustrated in Figures 16 and 17 respectively.

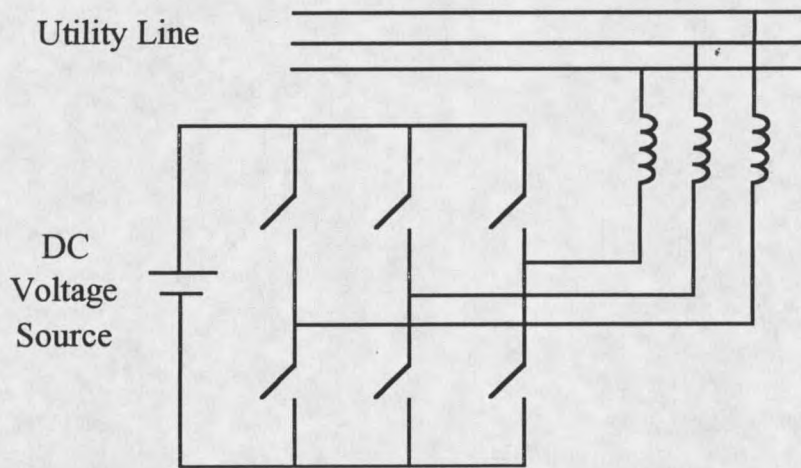


Figure 16. Simplified schematic of a pulse width modulated three phase VSI.

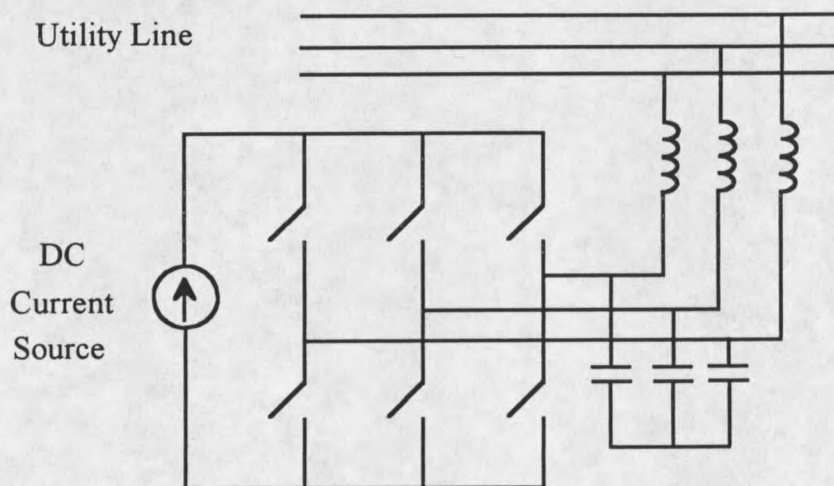


Figure 17. Simplified schematic of a pulse width modulated three phase CSI.

In either case, independent dc voltage/current can be established and maintained through the separate dc sources as shown in the respective figures or a stand-alone capacitor/inductor can be used on the dc side and the dc voltage/current can be controlled through the gating signals to the inverter switches. PWM techniques such as selective harmonic elimination or sinusoidal PWM have been proposed in order to keep the inverter output harmonics to the minimum [18].

Although these topologies offer better performance, realization of this approach poses significant problems since they require forced commutated power devices which can sustain the voltage ratings of a typical utility line.

Hybrid Compensators

The variable voltage source type compensators discussed in the previous subsection offer better performance, but they require the ratings of the power devices to be of the order of a typical utility line. Various hybrid topologies have been reported in the literature [19-21] which combine a couple of power converters to handle the bulk power and to ensure the desired performance respectively.

Reference [19] presents a topology (Figure 18) which comprises a current source inverter handling high power with very low switching frequency, and a voltage source harmonic filter handling low power with a much higher switching frequency. The CSI is responsible for providing, on its ac side, the required amount of reactive current. The current magnitude thus controls the amount of reactive power flow through the converter.

The VSI is controlled as an active filter and its frequency spectrum profile is shaped such that it sinks all the harmonic currents of concern.

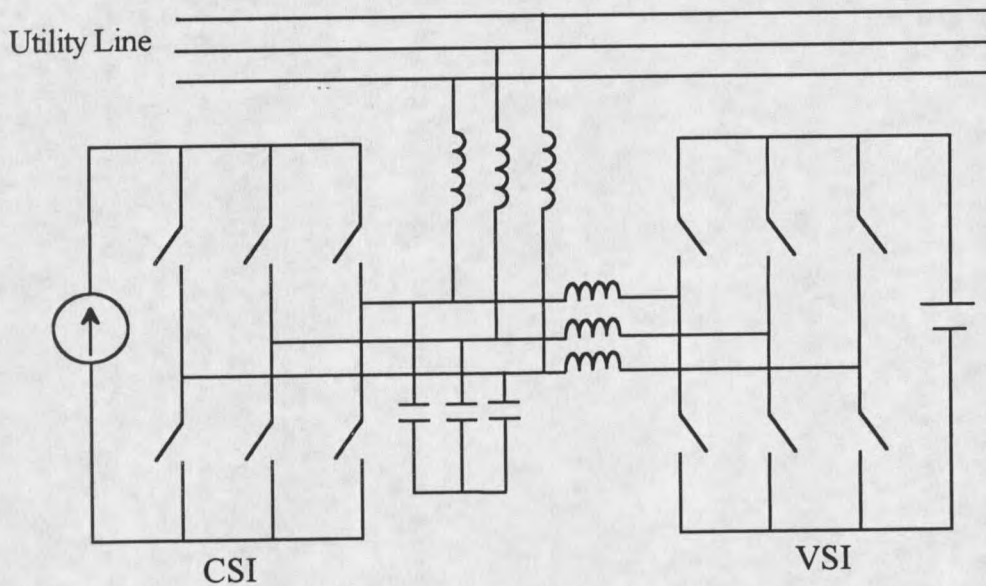


Figure 18. Simplified schematic of a hybrid compensator with VSI and CSI.

Topologies which are a hybrid of a MLI and a VSI have been proposed in [20,21]. A simplified schematic of this type of reactive compensator is illustrated in Figure 19. The reactive power exchange at fundamental frequency is handled by the MLI. [20] proposes the reactive power exchange at fundamental frequency is handled by the MLI. [20] proposes the transformer coupled MLI (Figure 13) while [21] proposes the H-bridge type of topology (Figure 15) to serve the purpose. The VSI is controlled to inject a current which cancels the harmonics in the load current and the harmonics generated by the MLI. Thus in addition to providing the reactive power, this topology also acts as a harmonic compensator.

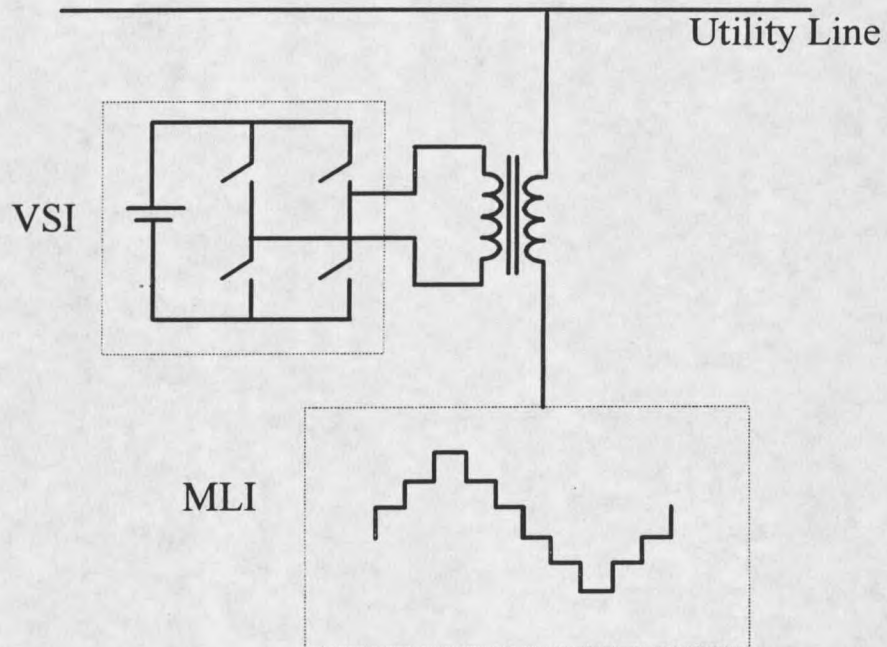


Figure 19. Simplified schematic of a hybrid compensator with VSI and MLI.

Reference [10] has recently presented a hybrid topology which combines a pulse width modulated VSI with a thyristor controlled SVC. A simplified schematic of this approach is illustrated in Figure 20.

This hybrid compensator consists of a VSI connected in series with a SVC. The power electronic VSI injects the sinusoidal current into the utility system corresponding to the required compensation. Since the VSI output is pulse width modulated, it ensures a low frequency harmonic free interface with the utility line. As the VSI is interfaced directly with the utility line, the voltage across it would be very high if it had been used alone. However, the SVC which is connected in series to it acts as a variable reactance and develops a fundamental voltage which is equal to the utility line voltage. This leaves

only a small residual harmonic voltage across the VSI and thus decreases its power rating. The present thesis deals with the investigations carried out on this hybrid topology for reactive power compensation.

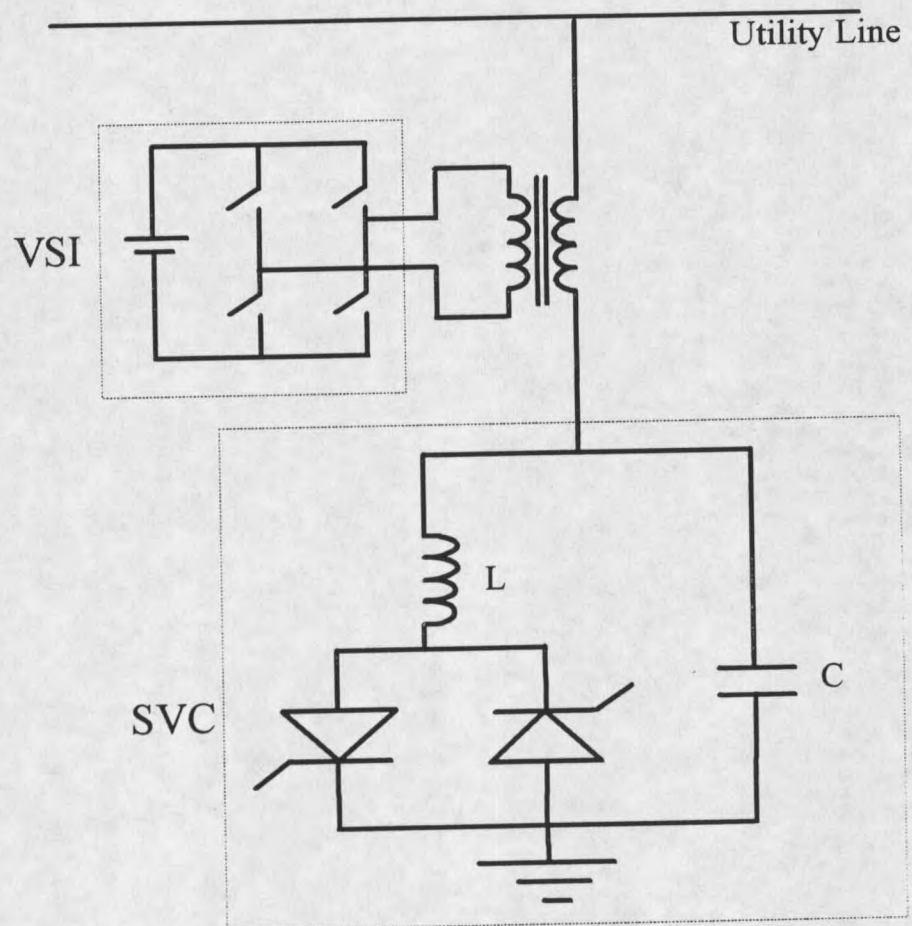


Figure 20. Simplified schematic of a hybrid compensator with VSI and SVC.

Comparison of Static Reactive Compensators

Table 1 tabulates the respective advantages and disadvantages of the different topologies for static reactive compensation. The selected performance attributes are power level, low frequency harmonic content and the complexity. The listed topologies include representatives of all the aforementioned categories of the reactive power compensators viz. variable reactance, variable voltage source and hybrid compensators.

Table 1. Qualitative comparison of static reactive compensators.

	Power level	Low frequency harmonic content	Complexity
Conventional Static VAR Compensator	Very High	Substantial	Very Simple
PWM Controlled Variable Reactance	Low	None	Simple
Voltage Source Inverter	Low	None	Complex
Current Source Inverter	Low	None	Complex
Multilevel Inverter	High	None	Highly Complex
MLI + VSI	Very High	None	Highly Complex
VSI + CSI	Low	None	Complex
VSI + SVC (Proposed hybrid)	Very High	None	Complex

Summary

This chapter has presented a survey of some of the static reactive power compensation techniques presented in the literature. In the preceding sections, various topologies proposed in the past for reactive compensation have been reviewed. The classification and a qualitative comparison of the static reactive compensators presented so far illustrates that the desirable features in a static reactive compensator are :

- i. it should be able to provide the required reactive compensation;
- ii. it should not exchange harmonic contents with the utility line;
- iii. it should be able to be interfaced on the utility line directly;

Conventional SVC can provide the required reactive compensation and also it can be interfaced on a utility line with relative ease. But it injects a low frequency harmonic content on account of the switching of the thyristors. As an alternative approach which has superior performance attributes in terms of harmonic current injection, some power converters based on PWM have been presented. Although these topologies offer better performance, realization of this approach requires power devices which can sustain large voltage ratings. The use of multiple devices in multilevel converters instead of the usual two level types in order to scale these converters to higher power levels obviates the necessity of high power rating devices. However, there are a number of issues such as dc bus stability and modulation strategy which are still to be addressed [17].

So, overall one may notice that the conventional SVC can handle the bulk power but it introduces the low frequency harmonic content. Conversely, the PWM controlled topologies offer better performance, but the maximum power level the self commutated devices can reach is limited. References [10,11] present a hybrid approach that combines the two to achieve each of their best features (high power level and an interface free of harmonic interaction) simultaneously. The investigations on the feasibility of such an approach which combines the bulk power handling SVC and the low power converter is treated in this thesis in the following chapters.

CHAPTER 3

HYBRID STATIC REACTIVE POWER COMPENSATOR

Introduction

As mentioned in the concluding section of the previous chapter, the Static VAR Compensator (SVC) can provide the required reactive compensation and can handle the bulk power. But it introduces the low frequency harmonic content in the utility system on account of the thyristor switching. Furthermore, since the thyristors can be fired only in alternate half cycles, the response speed of the compensation is limited by this inherent time delay in the thyristor gating control. On the other hand, the approach employing Pulse Width Modulation (PWM) technique offers better performance, but the maximum power level the self commutated devices can attain is limited.

A hybrid approach that combines the two to achieve each of their best features (high power level and an interface free of harmonic interaction) simultaneously is presented in this chapter. The proposed approach combines a power electronic reactive current injector with a conventional SVC. The following section discusses the evolution process and the operation of the hybrid compensator. It is followed by a section which describes various reactive elements and provides guidelines for their selection. The

constraints on the current injector are listed in next section. The control and the start up strategies are presented in the final sections.

Evolution and Operation of the Hybrid Reactive Power Compensator

A capacitor is the simplest element which one may use for the purpose of reactive power compensation. This is illustrated in Figure 21.

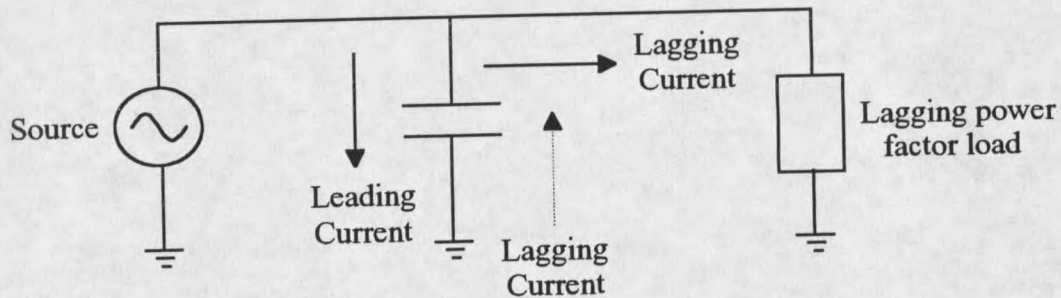


Figure 21. Reactive compensation by a simple capacitor.
The capacitor draws leading current; in effect supplies lagging current.

As is well known and shown in Figure 21, the capacitor draws in the current with a leading power factor. In other words, it can be said that the capacitor is supplying the current with a lagging power factor. Hence when used as depicted in Figure 21, the capacitor can supply the reactive power which is demanded by the lagging power factor load. This would obviate the generation of reactive power by the source. However, the problem with this strategy is that the reactive power demand is often varying on account of being load dependent. So, in order to be able to use this strategy, in principle, the

capacitor needs to be rated for the worst case reactive power demand. This calls for the need of a compensator which can provide variable compensation depending on the load. A conventional thyristor based SVC is one of the most popular techniques employed for this purpose. However, as reviewed in the last chapter, the principal drawback of the conventional SVC is that it injects the low frequency harmonic currents into the utility line. These harmonics are generated on account of thyristor switching in Thyristor Controlled Reactor (TCR).

As mentioned in Chapter 1 (Introduction), the principal objective for controlling the reactive power flow is to regulate the voltage in the utility distribution system. So rather than connecting a passive element such as capacitor to supply the reactive power, an active approach would be to use a Reactive Current Injector (RCI) which shall control the reactive current as shown in Figure 22.

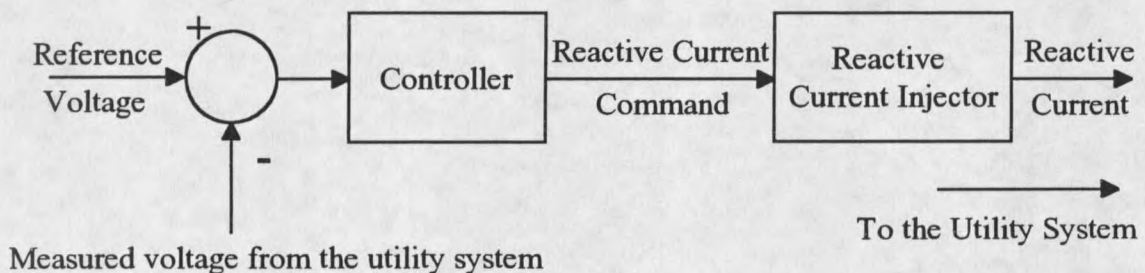


Figure 22. Voltage regulation by reactive current injection. Reactive Current Injector actively controls the reactive current; consequently regulates the voltage in the utility distribution system.

As illustrated in the Figure 22, the reference voltage is compared to the actual voltage in the utility distribution system. The error drives the controller which generates the reactive current command. This command is fed to the RCI which synthesizes the reactive current and feeds it in the utility system. The working principle of this approach is demonstrated in Figure 23.

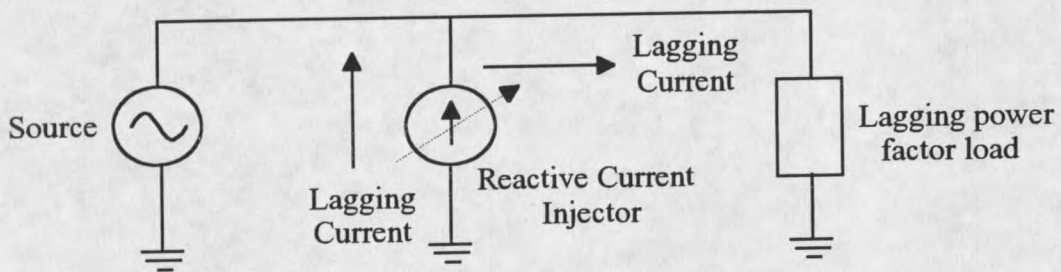


Figure 23. Variable reactive compensation by RCI.

A RCI as shown in Figure 23 which is capable of supplying variable reactive current would be sufficient to cater to the needs of the lagging power factor load. Moreover, as this current injector would generate sinusoidal waveforms, any harmonic interaction with the utility line may be prevented. The sinusoidal current synthesis can be done using any of the conventional topologies of the pulse width modulated power converters [22]. But it may be observed that the power rating of such a current injector would be enormous as it is directly interfaced with the utility line. Furthermore, the realization of RCI becomes difficult as it would require the power devices which can switch at a very high frequency and the same time are capable of blocking the voltage of the order of transmission or distribution levels [9].

This problem can be solved by introducing an impedance in series with the current injector (Figure 24). The reactive current which is injected in the utility system, will also flow through this impedance and thus create a voltage bias at point A as shown. The impedance should be controlled such that for the entire range of the injected current, the voltage developed by this impedance is equal to the utility line voltage as illustrated in Figure 24.

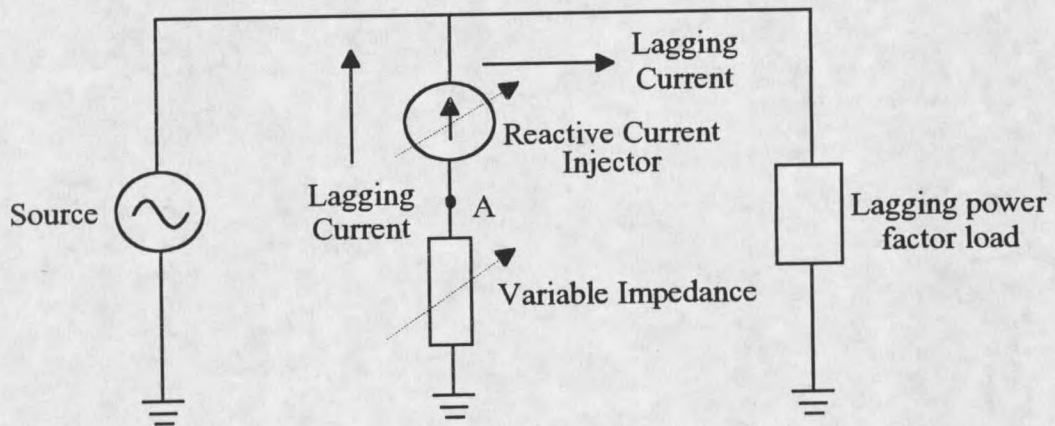


Figure 24. Reactive compensation by a series connection of RCI and a variable impedance; A variable impedance in series to give a voltage bias to the reactive current injector.

Thus, the voltage stress across the current injector will be null, if one controls the variable impedance accurately. The variable impedance can be realized by reactive elements to diminish the power loss. An ordinary TCR can be used as a variable inductance for this purpose. But, in order to have leading as well as lagging compensation capability, one needs a capacitive reactance also. Thus, a TCR with a capacitor connected in parallel, which is a conventional SVC can be an excellent candidate for the required

variable impedance. A RCI based compensator system which uses SVC as a variable impedance is illustrated in Figure 25.

By combining a self commutated device based current injector with a thyristor controlled voltage absorbing network, one can accomplish the reactive power compensation at high power levels with utility interface free of harmonic interaction.

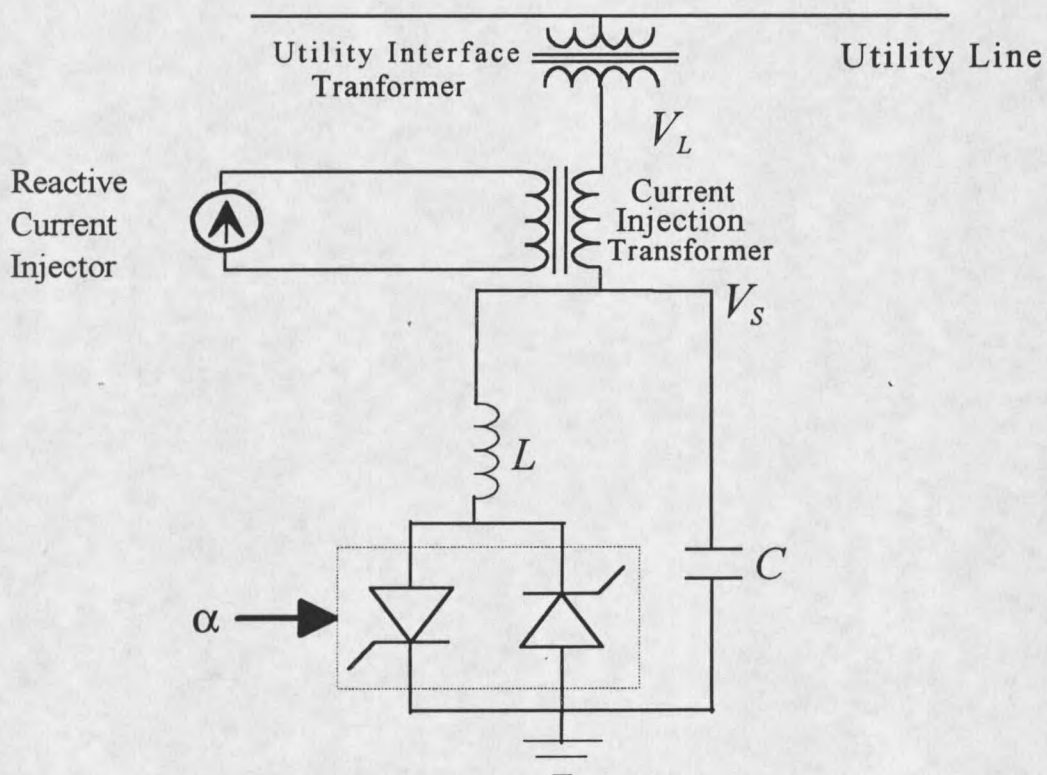


Figure 25. Simplified schematic of the hybrid static reactive power compensator.

As shown in Figure 25, the RCI injects the reactive current through the Current Injection Transformer (CIT). This current is supplied into the utility line through the Utility Interface Transformer (UIT). The variable impedance, as may be seen, is formed by

the conventional SVC. In this configuration, the impedance variation is carried out by means of thyristor firing angle (α) control. With suitable firing angle control, the equivalent impedance of the SVC can be regulated such that, for a given injected reactive current, the voltage developed by the SVC (V_s) is equal to the utility line voltage (V_L). This reduces the power rating of the current injector and also the voltage stress on the devices used to synthesize the reactive current. Moreover, as the current injected into the utility system is actively controlled, the harmonics generated in the SVC on account of thyristor switching are isolated from entering into the utility system. This forms the basic principle of the hybrid static reactive power compensator as investigated in this thesis.

The RCI is controlled to inject a sinusoidal current with magnitude I corresponding to the desired compensation level. Simultaneously, the SVC is controlled such that it generates the same amount of fundamental reactive current explained as follows :

The utility line voltage at the point of compensation is assumed to be $V_L \sin \omega t$ where ω is the supply frequency. As the injected reactive current has a phase difference of 90° with the line voltage, it may be assumed that the current injected from the compensator can be represented to be as $I \cos \omega t$. The variable I may be a positive (representing leading compensation) or negative (representing lagging compensation) quantity with its value representing the desired compensation level. By Kirchoff's voltage law, the peak voltage across the current source V_{CS} is given by

$$V_{CS} = V_L - V_S \quad (3.1)$$

where V_S is the peak value of the fundamental component of the SVC voltage.

The value of V_{CS} determines the power rating of the power electronic current injector. It may be noticed that the TCR current can be controlled through its firing angle (α), such that the value of the SVC voltage V_S is equal to the line voltage V_L . Under this condition, the fundamental voltage across the SVC will be equal to the utility line voltage and the current injected into the utility line will still be purely sinusoidal. Hence, the power electronic converter will see only the residual harmonic voltage which reduces its rating considerably. Thus SVC is used as a variable reactance to absorb the line voltage with the firing angle as a controlling parameter to vary the reactance.

The system now being current controlled, isolates the harmonic interaction between the utility line and the SVC. The harmonics which were caused by the thyristor switching are still present; however these generated harmonics are now forced to flow in the capacitor which is connected in parallel. This may be illustrated using the equivalent circuits of this hybrid compensator at fundamental and harmonic frequencies are as shown in Figure 26.

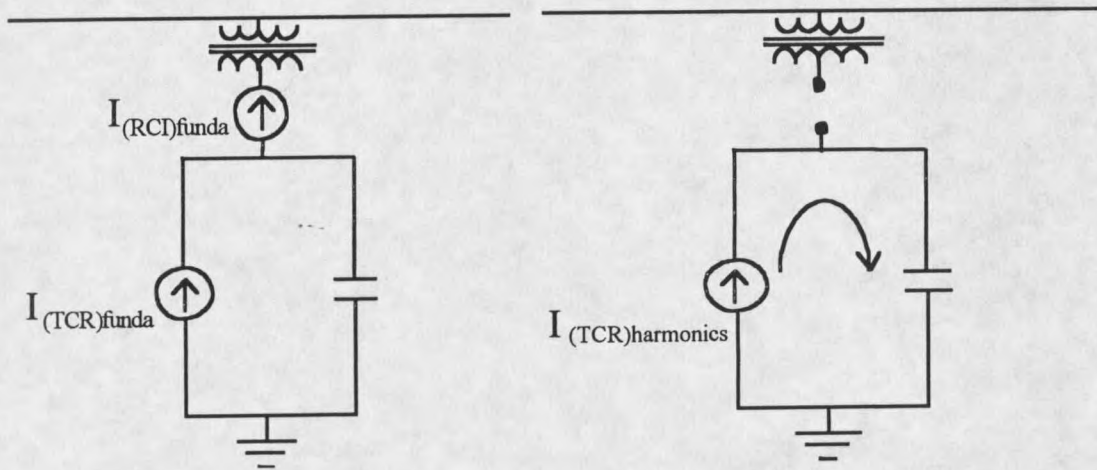


Figure 26. Equivalent circuits of the hybrid reactive compensator;
 (a) For fundamental frequency; (b) For harmonic frequencies;

It may be noticed from Figure 26(a) that the RCI is controlled to supply the fundamental reactive current. So the overall current in the SVC is forced to be purely sinusoidal and only the fundamental component of the current generated by the TCR is allowed to pass in the utility system.

While as illustrated in Figure 26(b), the equivalent impedance of the RCI is infinite at harmonic frequencies. Hence, any harmonics generated in the TCR current because of thyristor switching are drained in the capacitor and the utility line is isolated from any harmonic interaction.

Selection of Reactive Elements

As explained in the last section, the SVC is used as a variable reactance in this hybrid compensator. The function of the SVC is to develop the voltage, the fundamental component of which is equal to the utility line voltage for a given reactive current as shown in Figure 27.

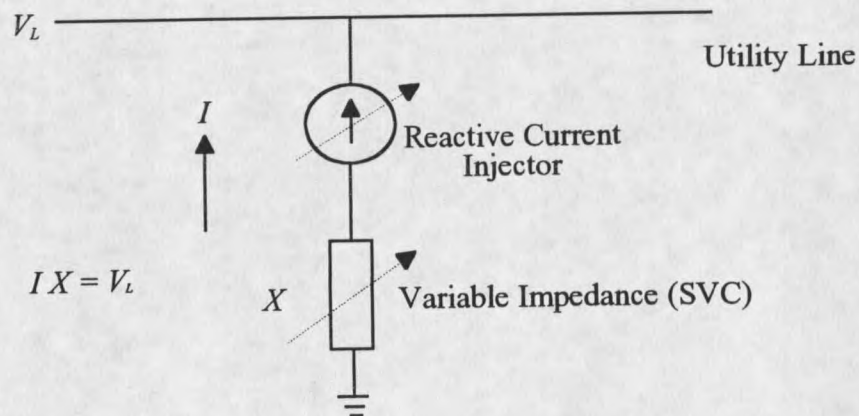


Figure 27. Functional representation of SVC in the hybrid reactive compensator; SVC is used as a variable impedance such that the voltage across it is equal to the utility line voltage.

For any given reactive current of amplitude I , the equivalent impedance of the SVC should be such that the fundamental voltage developed across it is equal to the utility line voltage V_L . If this condition is satisfied, then the residual voltage across the RCI is only because of the harmonic content in the SVC which will, in principle, reduce the stress on the devices used in the power electronic current injector.

The firing angle (α) and consequently the conduction angle (σ) of the thyristors is the controlling parameter to vary the equivalent reactance of the SVC. The relation between the equivalent reactance X_{eq} of a current sourced SVC with inductance (L) and capacitance (C) and the conduction angle σ is derived in the appendix. This relation is given as

$$X_{eq} = X_C \left\{ 1 - \frac{A(\sigma + \sin \sigma)}{\pi} + \frac{4A \cos^2(\frac{\sigma}{2}) K \tan(\frac{K\sigma}{2}) - \tan(\frac{\sigma}{2})}{\pi (K^2 - 1)} \right\} \quad (3.2)$$

where $K = \frac{\omega_o}{\omega}$ (3.3)

$$\omega_o^2 = \frac{1}{LC} \quad (3.4)$$

$$A = \frac{\omega_o^2}{\omega_o^2 - \omega^2} \quad (3.5)$$

$$X_C = \frac{1}{\omega C} \quad (3.6)$$

$$\frac{\sigma}{2} = \pi - \alpha \quad (3.7)$$

and where ω is the supply frequency;

The design procedure for the individual reactive components of the SVC is identical to that of a conventional SVC and is discussed in [1]. The expressions to design the reactance of inductor (X_L) and capacitor (X_C) are as follows,

$$X_C = \frac{V_L}{I_{lead(max)}} \quad (3.8)$$

$$X_L = \frac{V_L}{I_{lag(max)} - I_{lead(max)}} \quad (3.9)$$

where, V_L is the utility line voltage;

ω is the line voltage frequency;

$I_{lag(max)}$ is the maximum current for lagging compensation;

and $I_{lead(max)}$ is the maximum current for leading compensation;

The capacitor should be rated for the utility line voltage, while the current rating for the inductor depends upon the respective compensation currents. It should be rated for the value equal to the sum of maximum leading and lagging compensation currents.

An example system which can provide a maximum of 40 % reactive compensation (both, lagging and leading) is designed for a utility system having a line voltage of 1 per unit. The values of the inductive and capacitive reactance for this compensator system, as found from the expressions (3.8) and (3.9), are 1.25 per unit and 2.5 per unit respectively. With these values of the reactive elements and from the equivalent reactance expression (3.2), the effective impedance of the SVC is plotted in Figure 28.

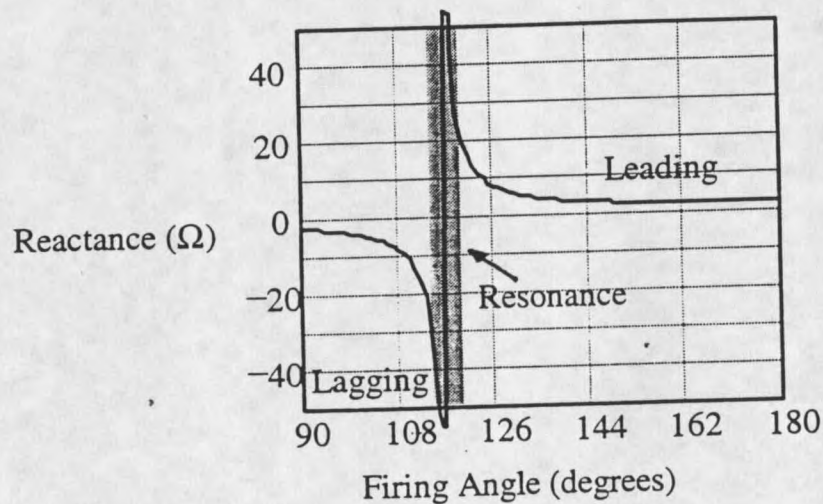


Figure 28. Plot of equivalent reactance of the current fed SVC v/s the firing angle.

As one may expect, the impedance is seen to be negative in the lagging compensation zone and positive in leading compensation zone. It may be noticed that for smaller firing angles, that is for higher conduction angles of thyristor, the inductance is the dominant component in the SVC circuit, which makes the compensation to be lagging (inductive). On the other hand, for bigger firing angles, conduction time is very small, which makes the effective inductance to be small, and hence the compensation is leading (capacitive). The region which demarcates between the leading and lagging compensation is the area where the capacitance and the TCR inductance resonate. Since it is a parallel L-C network, the equivalent impedance at resonance is infinite. Thus the variation of the equivalent impedance of the current sourced SVC can be accomplished with the variation in the firing angle. So, the SVC can be used as a variable impedance.

Constraints on the Reactive Current Injector

The power electronic current injector is required to supply the required amount of the fundamental reactive current through the current injection transformer. The ratings of the transformer and the power converter may be determined using the harmonic injection from the TCR and the design relationships as presented in [10]. As explained earlier in this chapter, the current generated in the current source and the injection transformer is equal to the required compensation current. But the voltage across them is small and is equal to the residual harmonic voltage developed across the SVC. Reference [10] gives the expression for the n^{th} order harmonics generated in SVC voltage (V_n) as follows

$$V_n = \frac{4V}{\pi\omega^2 LC} \left[\frac{\sin(\alpha)\cos(n\alpha) - n\cos(\alpha)\sin(n\alpha)}{n^2(n^2-1)} \right] \quad (3.10)$$

The total rms harmonic content (V_h) is then found by

$$V_h = \sqrt{\sum V_n^2} \quad (3.11)$$

So the apparent power rating (S) for the current injector and the series injection transformer may be calculated as

$$S = V_h I_C \quad (3.12)$$

where I_C is the required compensation current.

Thus, the required current injector should be able to source the required amount of the compensation current and should be rated for the power as given by expression (3.12). Various topologies which would serve the purpose are presented in literature [18,20,21].

Control Strategies

The proposed hybrid reactive power compensator combines a power electronic current injector with a thyristor controlled SVC. In order to reduce the voltage stress on the power electronic current injector, the fundamental voltage across the SVC should be regulated such that it is equal to the utility line voltage at any instant. Since the compensation reactive current is variable, this can be accomplished by varying the impedance offered by the SVC. The variation of the SVC impedance is realized by varying

the firing angle of the thyristors. So, in order to vary the impedance of the SVC, the firing angle α is used as the control variable. This, in effect, changes the equivalent inductance in the TCR, which ultimately affects the overall impedance.

Thus the Firing Angle Generator (FAG) is configured so that the impedance of the SVC (TCR connected in parallel with a Capacitor) at any operating condition is such that the fundamental voltage developed across the SVC is equal to the line voltage. Once the relationship between the firing angle and the impedance of the SVC is known, it is rather straightforward to realize the control objective. The fundamental SVC voltage V_s and equivalent SVC reactance X_{eq} are related by the compensation current I_c as follows

$$V_s = I_c X_{eq} \quad (3.13)$$

The equivalent impedance of the current sourced SVC operating with a conduction angle of σ is given by expression (3.13). Simplification of this expression to obtain a closed form relationship for α in terms of I_c is not possible. However, a look-up table for determining α for different values of the current I_c can be easily constructed. A simplified block schematic of the control system to regulate the injected reactive current and the firing angle of the SVC is illustrated in Figure 29.

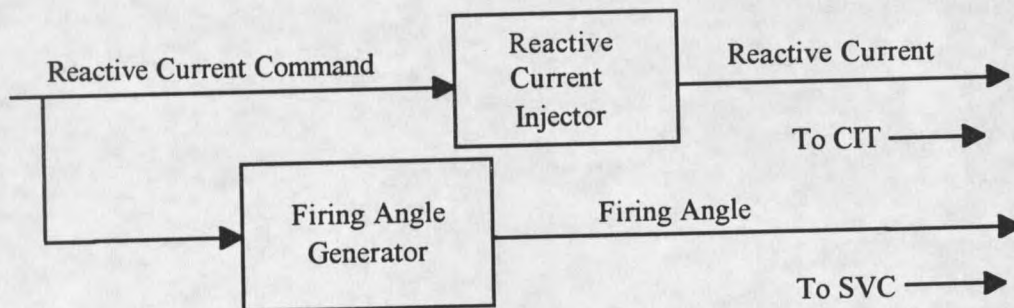


Figure 29. Simplified block schematic of the proposed control system.

The reactive current command is issued to the Reactive Current Injector (RCI) to synthesize the reactive current. This reactive current is injected in the utility system and the SVC through the Current Injection Transformer (CIT). The Firing Angle Generator (FAG) takes the current command and computes the required firing angle for the SVC such that the fundamental voltage across the SVC is equal to the utility line voltage for the given reactive current.

Start-up and Scheduling Strategy

The relationship between the firing angle and the SVC voltage as illustrated in Figure 28 is valid under the static conditions. But the dynamics of the system exhibit nonlinearities which could be attributed to thyristor switching [7]. A stability analysis of the system presented in the following chapter indicates that a periodical steady state solution may not exist for the system when it is delivering fully leading compensation. Preliminary investigations on the system using simulations also indicated such conditions during which the system operation lead to large transients in the SVC voltage.

As will be demonstrated in the following chapter of stability analysis, the eigen values of the discrete time dynamical equations of the system lie on the unit circle when the system is delivering its full capacity leading compensation. This indicates that a small disturbance at this operating point can cause loss of the periodic steady state solution. Hence it is proposed to start the system from the other end i.e. with full capacity lagging compensation. Once the system settles through the start-up, the compensation level may

be slowly ramped up as required. In addition, the SVC capacitor which may be at zero volts prior to the start-up needs to be charged upto the line voltage. This can be done by connecting it to the utility line through a charging resistor in series. This is illustrated in Figure 30.

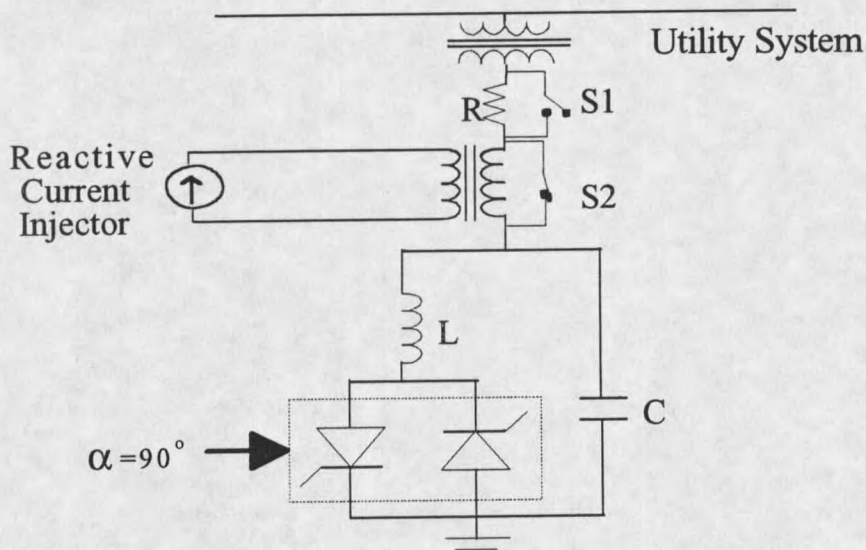


Figure 30. Precharging mode of the SVC capacitor at the start-up.

As shown in Figure 30, the switch S2 is closed and S1 is open at the start-up. This connects the capacitor directly to the utility line through a charging resistor (R). The Reactive Current Injector (RCI) is bypassed in this mode. The firing angle (α) of the thyristors is held at 90° such that the inductor is fully in the circuit. After the capacitor is charged and the system reaches steady state, the switch S1 is closed and S2 is opened. This bypasses the resistor and connects the RCI into the circuit. The system now acts as a

lagging compensator at its full capacity. After the system reaches steady state in this condition, the injected reactive current is slowly ramped up to the required compensation level. A start-up and scheduling strategy is thus developed to ensure that the system keeps off from losing the periodic steady state. Figure 31 illustrates the flow diagram of the proposed start-up and scheduling strategy.

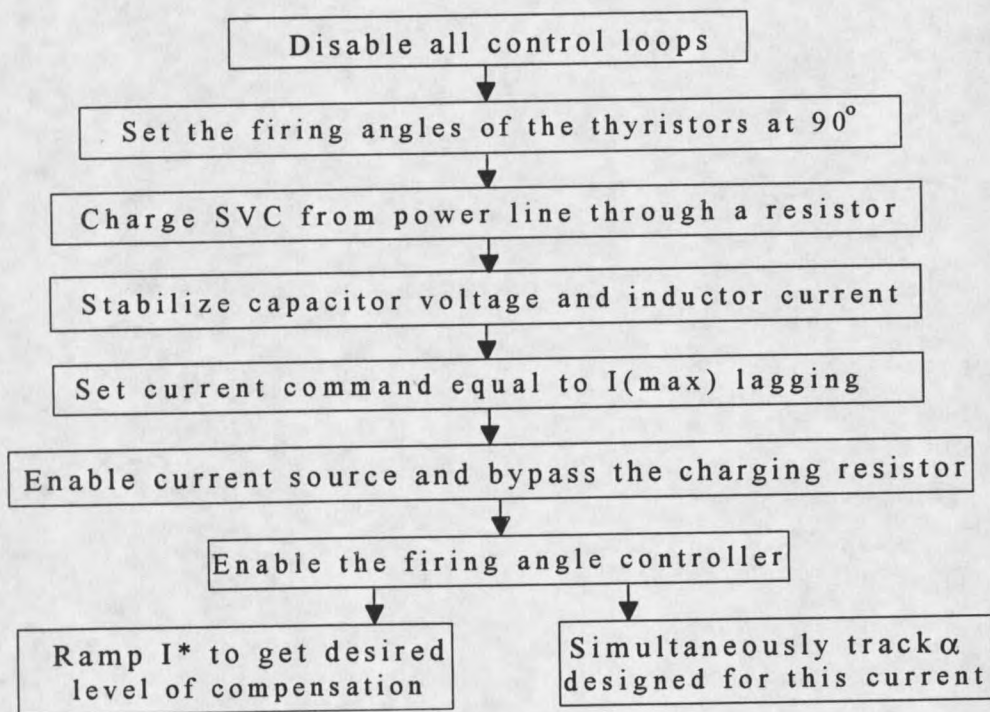


Figure 31. Start-Up and Scheduling strategy.

CHAPTER 4

STABILITY ANALYSIS OF A CURRENT FED STATIC VAR COMPENSATOR

Introduction

As described in the last chapter, the proposed hybrid static reactive power compensator combines a power electronic Reactive Current Injector (RCI) and a thyristor controlled Static VAR Compensator (SVC). The RCI injects a reactive current in the utility system according to the compensation requirements. This current also flows through the series connected SVC which creates a voltage bias for the RCI. As the current injected into the utility system (and so also in the SVC) is actively controlled, the system can be said to be current regulated. The dynamics of a current controlled SVC are different from those of a conventional SVC [7]. In a current fed SVC, the current is forced into the SVC, and the voltage across it depends on the firing angle of the thyristors. The dynamics of a current fed SVC are similar to those of Advanced Series Compensator (ASC) where the SVC is connected in series with a utility line. The dynamics of the ASC have been studied and they have been concluded to be intricate and highly non-linear [7]. As the topologies of the current fed SVC and ASC are closely related, similar behavior may be expected of the dynamics of the SVC. Hence they are investigated in this chapter. The following section presents a brief description of the system and the details of the stability analysis.

Stability Analysis

Figure 32 shows a simplified schematic of the proposed hybrid compensator system. The Reactive Current Injector (RCI) injects the reactive current through the Current Injection Transformer (CIT). The current is supplied into the utility system through the Utility Interface Transformer (UIT). The same current also flows in the series connected Static VAR Compensator (SVC).

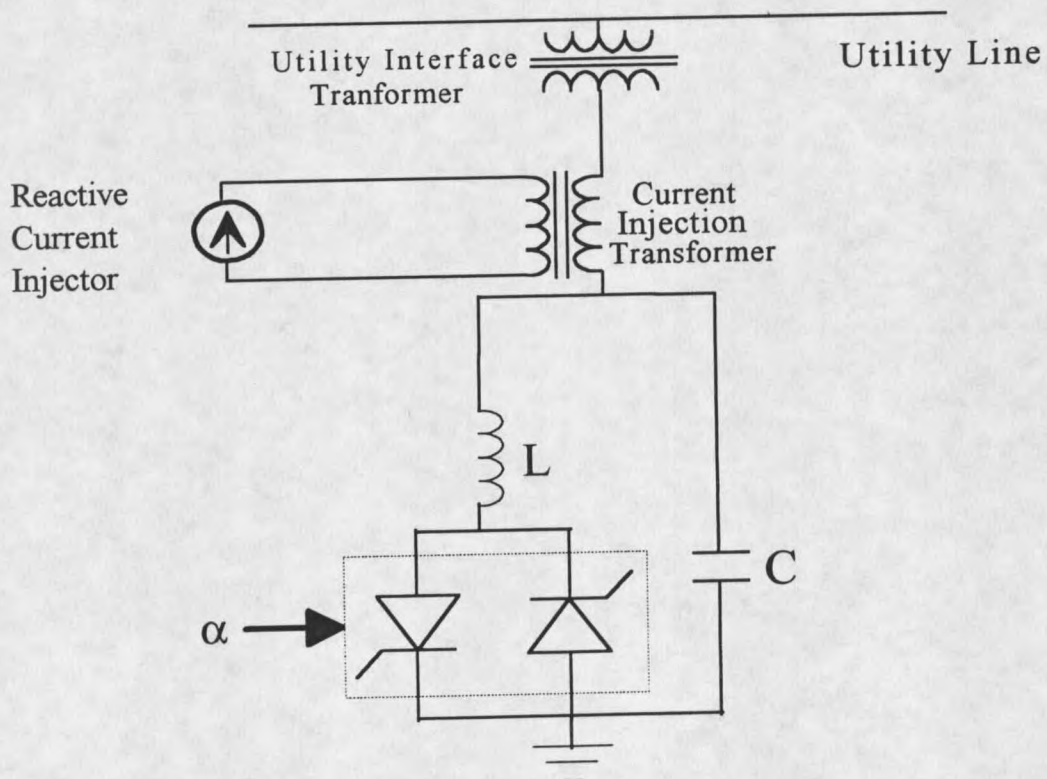


Figure 32. Simplified schematic of the hybrid reactive compensator.

As is evident from Figure 32, the compensator system is current controlled. The current in the utility system and the SVC is regulated by the RCI. A simplified schematic of the current fed SVC can be drawn as illustrated in Figure 33. It may be seen that the current source injects a current I into the SVC.

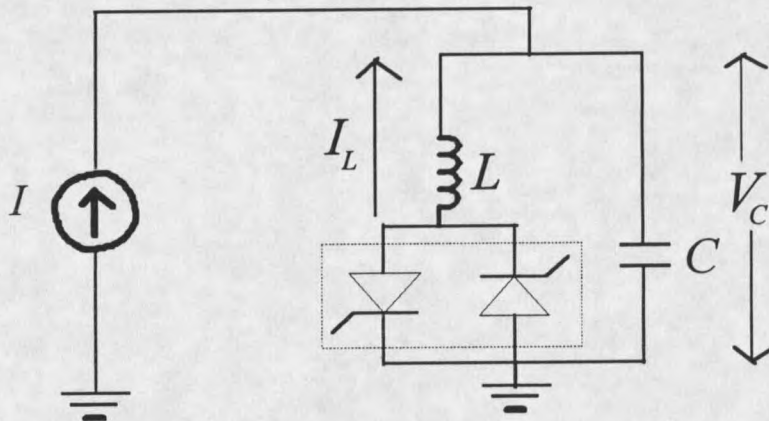


Figure 33. Simplified schematic of a current fed SVC.

Figure 34 shows the typical TCR current and SVC voltage waveforms of a current fed SVC. It may be noticed that the voltage across the SVC in the current fed system is highly distorted. This is opposite to what is observed in a conventional voltage sourced SVC (Figure 9) where the SVC voltage was sinusoidal.

The harmonic content in the SVC voltage is observed here because the system is current controlled. The current in the capacitor is equal to the difference between the injected current (which is regulated) and the TCR current (which depends on the state of the thyristors). So when the thyristors are off, the TCR current is zero and entire injected current is flows through the capacitor. As this current is controlled to be sinusoidal, the

voltage developed across the capacitor is also sinusoidal and is free from harmonic content. But when the thyristors are conducting, the capacitor current is equal to the difference between the injected current and the TCR current (which is present only for a fraction of the power cycle). This introduces harmonic content in the capacitor current which in turn leads to the distortion in the capacitor voltage. Hence the operation of the current fed SVC can be seen to be different than that of a conventional SVC.

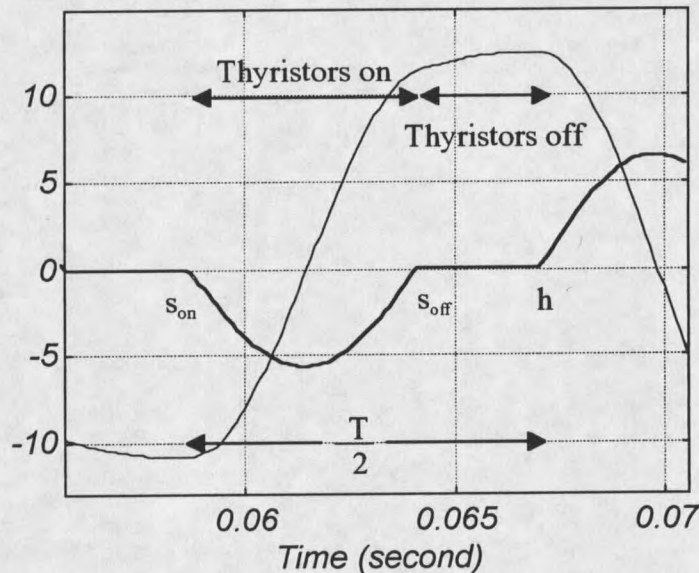


Figure 34. Typical capacitor voltage (thin trace) and TCR current (thick trace) waveforms.

From Figure 34, it may be observed that the thyristors are fired at instant s_{on} . They turn off as the current through them reaches zero at the instant s_{off} . The thyristors are again fired at instance h in the next half cycle. Thus the time interval between s_{on} and h is equal to half the time period of the power cycle.

For the purpose of analysis, the capacitor voltage (V_C) and the inductor current (I_L) may be selected to be the states of the system. The state equation of the current fed SVC system when the thyristor switches are closed; i.e. in the time interval (s_{on} , s_{off}) is

$$\frac{dx}{dt} = Ax + bu \quad (4.1)$$

where

$$x = \begin{bmatrix} I_L \\ V_C \end{bmatrix} \quad (4.2)$$

$$A = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & 0 \end{bmatrix} \quad (4.3)$$

$$b = \begin{pmatrix} 0 \\ \frac{1}{C} \end{pmatrix} \quad (4.4)$$

and

$$u = I \quad (4.5)$$

The solution to this differential equation in the interval (s_{on} , s_{off}) is

$$x(s_{off}) = e^{A(s_{off}-s_{on})}x(s_{on}) + \int_{s_{on}}^{s_{off}} e^{A(s_{off}-\tau)} bu(\tau) d\tau \quad (4.6)$$

Similarly, the state equation for the case when the thyristors are off; i.e. in the time interval (s_{off} , h) can be written as

$$\frac{dy}{dt} = PAQy + Pbu \quad (4.7)$$

where

$$y = V_C \quad (4.8)$$

and

$$P = Q^T = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (4.9)$$

The solution to this differential equation in the interval (s_{off}, h) is

$$y(h) = e^{PAQ(h-s_{off})} P e^{A(s_{off}-s_{on})} Q y(s_{off}) + \int_{s_{off}}^h e^{PAQ(h-\tau)} P b u(\tau) d\tau \quad (4.10)$$

At the switching instances s_{on} and s_{off} , the states are related by the projection matrices [7] P and Q as follows

$$x(s_{on}) = Q y(s_{on}) \quad (4.11)$$

$$y(s_{off}) = P x(s_{off}) \quad (4.12)$$

Hence from expressions (4.6), (4.10-12)

$$\begin{aligned} y(h) &= e^{PAQ(h-s_{off})} P e^{A(s_{off}-s_{on})} Q y(s_{on}) \\ &+ \int_{s_{on}}^{s_{off}} e^{PAQ(h-s_{off})} P e^{A(s_{off}-\tau)} b u(\tau) d\tau + \int_{s_{off}}^h e^{PAQ(h-\tau)} P b u(\tau) d\tau \end{aligned} \quad (4.13)$$

Substituting from expressions (4.2-5), (4.8-9) we get

$$\begin{aligned} V_C(h) &= \cos(\omega_n(s_{off}-s_{on})) V_C(s_{on}) \\ &+ \int_{s_{on}}^{s_{off}} \frac{1}{C} \cos(\omega_n(s_{off}-s_{on})) I(\tau) d\tau + \int_{s_{off}}^h \frac{1}{C} I(\tau) d\tau \end{aligned} \quad (4.14)$$

$$\text{where} \quad \omega_n^2 = \frac{1}{LC} \quad (4.15)$$

Linearizing the expression (4.14) with the assumption that the current source is stiff, we get the incremental value of the capacitor voltage (ΔV_C) as

$$\Delta V_C(h) = \cos(\omega_n(s_{off} - s_{on}))\Delta V_C(s_{on}) \quad (4.16)$$

So the Jacobian of the single phase current fed SVC system for the half period of operation is

$$J = \cos(\omega_n(s_{off} - s_{on})) \quad (4.17)$$

The relation between the switching instances s_{on} , s_{off} and the conduction angles of the thyristors σ can be given as

$$\sigma = \omega(s_{off} - s_{on}) \quad (4.18)$$

where ω is the supply frequency;

So the Jacobian in terms of the conduction angle (σ) is

$$J = \cos\left(\frac{\omega_n}{\omega}\sigma\right) \quad (4.19)$$

This can also be expressed in terms of firing angle (α) as

$$J = \cos\left(2\frac{\omega_n}{\omega}(\pi - \alpha)\right) \quad (4.20)$$

The eigen values of the Jacobian matrix determine the stability of a system. When the eigen values are within the unit circle, they signify that the system is locally stable [23]. For this particular system, the Jacobian is just a single element. Hence the eigen value of

the Jacobian matrix is simply the value of this element itself. When this value lies within a unit circle for a given operating point, it means that there exists a steady state periodic solution for the system equations.

It may be observed that as the firing angle (α) approaches 180° or π radians; or when the conduction angle (σ) approaches zero, the value of the Jacobian is close to unity. This is the case when the compensator system is in fully capacitive zone or in the maximum leading compensation region. From this analysis, it is evident that in the region where the firing angle (α) approaches 180° , there are chances that the steady state periodic solution does not exist for the given system equations. This shall be shown in the simulation results in the following chapter that the system indeed exhibits big transients and there is no periodic steady state solution in such cases.

CHAPTER 5

MODEL OF THE HYBRID STATIC REACTIVE POWER COMPENSATOR

Introduction

The proposed hybrid static reactive power compensator consists of a power electronic Reactive Current Injector (RCI) and a conventional Static VAR Compensator (SVC). This hybrid system is modelled and simulated using MATLAB-Simulink software [24].

This chapter describes the modelling of the proposed hybrid static reactive power compensator. The following section presents an overview of the model and discusses the evolution of the basic building blocks of the system. The subsequent section describes the implementation of these blocks in MATLAB-Simulink.

Block Diagram Representation of the Hybrid Compensator

As mentioned in the above introduction, the proposed hybrid compensator combines a power electronic RCI and a thyristor based SVC. So, the system is primarily composed of three components viz. Reactive Current Injector (RCI), SVC and the Current Injection Transformer (CIT) as illustrated in Figure 35.

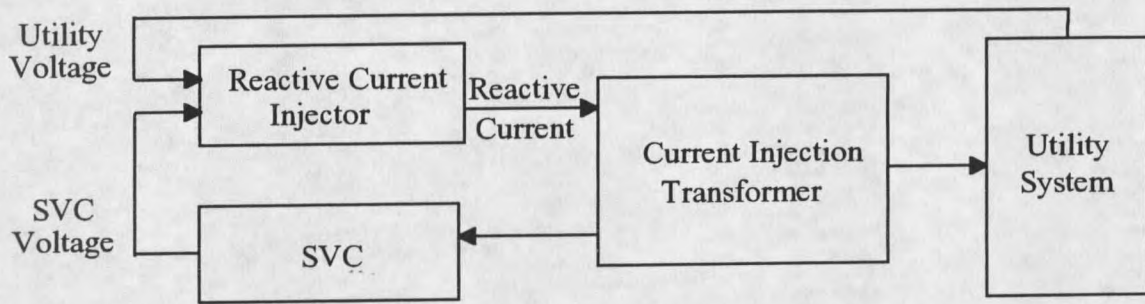


Figure 35. Block schematic illustrating the power circuit interconnections of the hybrid reactive compensator.

Figure 35 presents a block diagram representation of the basic principle of the hybrid static reactive power compensator. As depicted in this figure, the Reactive Current Injector (RCI) injects a reactive current in the utility system through the Current Injection Transformer (CIT). The same current also flows through the SVC which is connected in series with the RCI. In turn, the voltage as seen by this current injector is the difference between the utility line voltage and the voltage developed by the SVC. In order to minimize the voltage stress on the current source, one needs to tune the SVC such that for the given reactive current, the voltage developed by the SVC is equal to the utility line voltage. This is accomplished by varying the firing angle of the thyristors, which in effect varies the equivalent impedance of the SVC. This adds another block of Firing Angle Generator to the system. The Firing Angle Generator (FAG) is designed to be of a feedforward type which utilizes a lookup table. This lookup table computes the firing angle for any given reactive current command. Thus the overall system block diagram is as depicted in Figure 36.

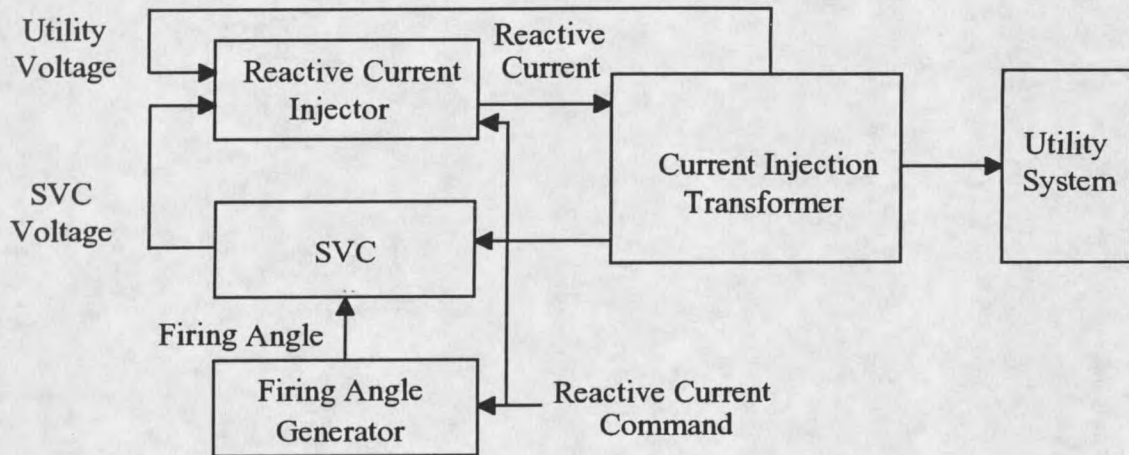


Figure 36. Simplified block schematic of the hybrid reactive compensator system.

MATLAB-Simulink Model of the Hybrid Compensator

The proposed hybrid compensator system is modelled in MATLAB-Simulink software [24]. The principal subsystems of the model are as illustrated in the Figure 37.

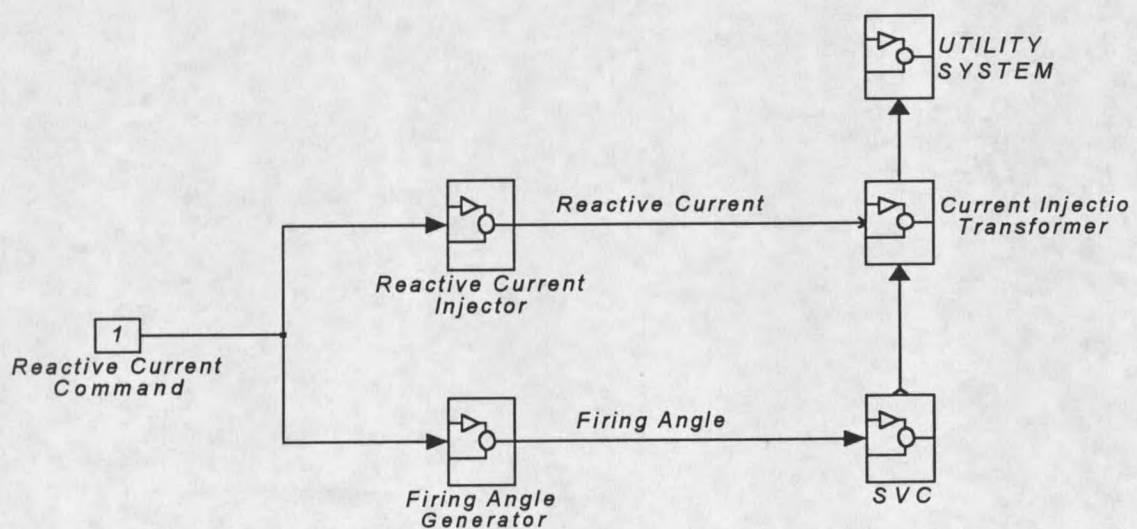


Figure 37. Block schematic illustrating the subsystems of the hybrid compensator model.

The *Reactive Current Injector* takes the *Reactive Current Command* input and synthesizes the *Reactive Current* for the required amount of compensation. This current is fed into the *UTILITY SYSTEM* through the *Current Injection Transformer*. The compensating current also flows through the *SVC* which is connected in series with the *Current Injection Transformer*. The *Firing Angle* for the *SVC* is issued by the *Firing Angle Generator* block. This *Firing Angle Generator* computes the *Firing Angle* using the *Reactive Current Command* as the reference.

Model of the SVC

The SVC consists of a Thyristor Controlled Reactor (TCR) with a capacitor connected in parallel to it. The capacitor model is built with a simple integrator and amplifier blocks which represent the differential equation governing its working. Figure 38 shows the model of the capacitor.

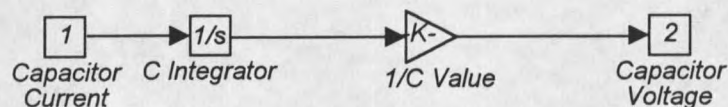


Figure 38. Model of the capacitor used in the SVC.

As illustrated in Figure 38, the input to the model of the capacitor is the *Capacitor Current*. The integral of the capacitor current gives charge which is divided by the value of capacitance to compute the *Capacitor Voltage*.

Figure 39 illustrates the model of the TCR. The inputs to this model are the firing angle α and the TCR Voltage. The TCR Voltage input also serves the purpose of generating the reference to detect the zero crossing. The output of the S-R Latch represents the state of the thyristor switch. Open state of the thyristors is simulated by resetting the latch which clamps the voltage across the inductor to zero. As may be observed, the model of the inductor is similar to that of the capacitor. The only differences are that, in this model, the $Inductor$ Voltage is integrated to provide the flux linkage which is then divided by the value of inductance to obtain the $Inductor$ Current output.

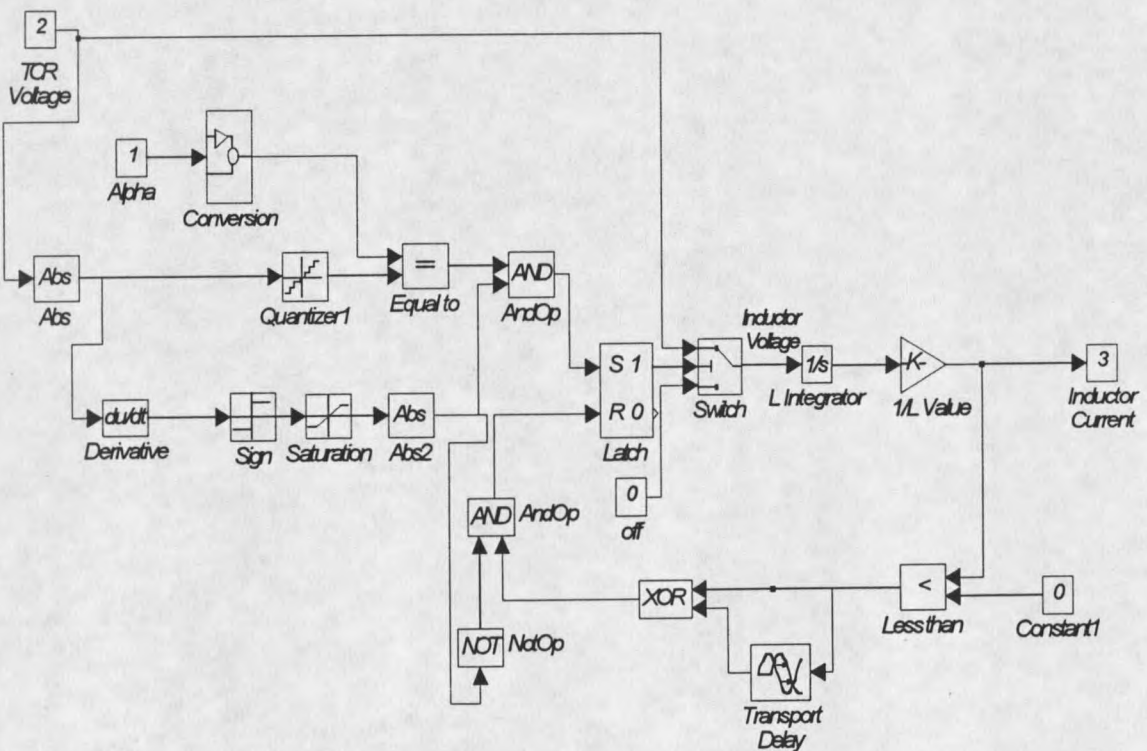


Figure 39. Model of the TCR used in the SVC.

To simulate the closed state of the thyristor, the firing angle *Alpha* is converted to the firing instant and is compared with the reference voltage. This reference voltage is computed by quantizing the absolute value of the *Inductor Voltage* input. When the firing instant matches with the reference value and the rate of change of the *TCR Voltage* input is positive, the S-R latch is set confirming that the thyristors are fired. This applies the *TCR Voltage* to the inductor model and the *Inductor Current* is computed.

The thyristor turn-off is accomplished by detecting the zero crossing of the inductor current. The *Transport Delay* and the *XOR* blocks are used in generating a pulse when the zero crossover of the inductor current is detected. This pulse output resets the S-R latch. It may be noticed that in this configuration, a pulse is obtained even when the thyristors are fired and the inductor starts conducting. Hence a cross checking loop is added which prevents the resetting of the S-R Latch by this pulse when the thyristors are fired.

Model of the *RCI* and the *CIT*

The *Reactive Current Injector* and the *Current Injection Transformer* are modelled as ideal current and voltage source respectively. A model of a chopper based current injector was simulated and tested in the preliminary investigations. It was observed that the dynamics of the current source were much faster than the response time of the rest of the system. This is because of the fact that the switching frequency of the devices used in the chopper was in the order of kHz. Whereas since the thyristors can be fired only in

alternate half cycles, there is an inherent time delay in the response speed of the rest of the system. Hence it was decided that the actual chopper based source be replaced by the MATLAB-Simulink ideal source model [24].

Model of the FAG

The *Firing Angle Generator* computes the *Firing Angle* for the SVC. In the steady state, the *Firing Angle* is generated by the lookup table which uses the *Reactive Current Command* as the reference. It also incorporates the start-up strategy and dynamic rate limiters to ensure that the command signals are quasi-static.

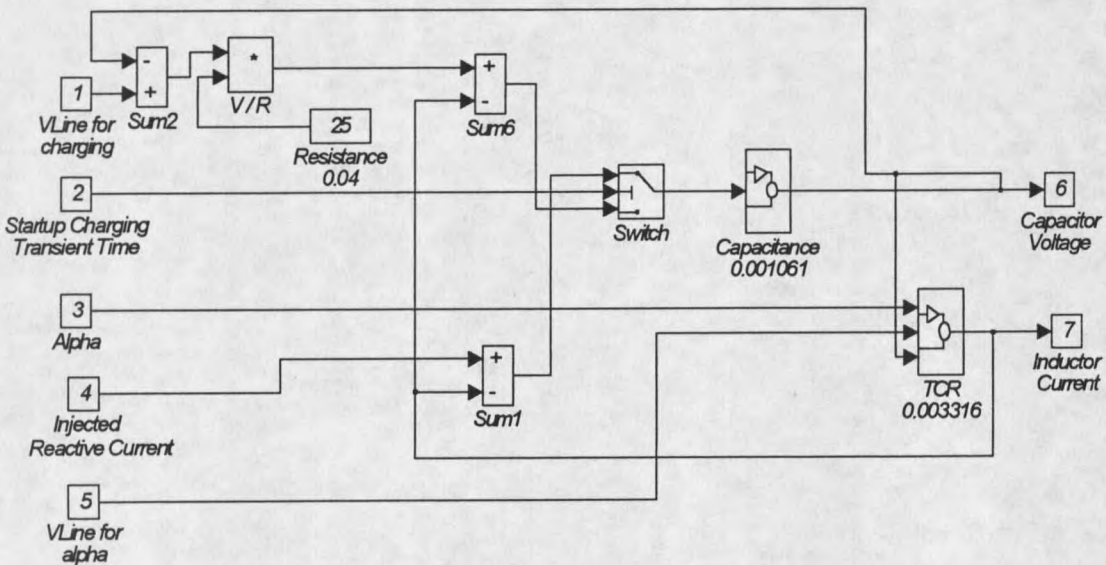


Figure 40. Model to simulate the start-up precharging algorithm.

Figure 40 shows a block schematic of the model used to implement the start-up charging strategy. The input *Startup Charging Transient Time* controls the *Switch*. The

other inputs are utility line voltage *VLine*, *Injected Reactive Current* and the firing angle *Alpha* respectively. The outputs of this block are the *Capacitor Voltage* and the *Inductor Current*.

The *Capacitance* block takes in the capacitor current and generates *Capacitor Voltage*. The *TCR* block takes in the TCR voltage (which is also same as the *Capacitor Voltage* in a SVC), *Alpha*, and *VLine* and computes the *Inductor Current*. The *Switch* has two inputs (top and bottom) which determine the capacitor current and one control (middle) which is governed by the *Startup Charging Transient Time* as has been mentioned earlier.

When the *Startup Charging Transient Time* input is low, the *Switch* selects the bottom input and the system is in the capacitor precharging mode. In this mode, the capacitor current is generated by the *VLine* in charging the *Capacitance* through the *Resistance* (Figure 30). After the charging process is over, the system reaches steady state and the *Startup Charging Transient Time* input goes high. This ends the capacitor charging mode and enables the reactive current injector. The capacitor current is now determined by the difference between the *Injected Reactive Current* and the *Inductor Current*.

After the capacitors get charged, some more time is allowed to enable the system reach the steady state; following which the static firing angle controller viz. Lookup Table is enabled. Figure 41 shows the Simulink model used to simulate the Lookup Table enable procedure.

As shown in this figure, two switches viz. *Switch1* and *Switch2* are used for selecting the *Reactive Current Command* and the firing angle *Alpha* respectively. During the start-up charging time interval, *Lookup Table Enable Time* input is low. So the firing angle is fixed by the *Startup Alpha* block at 90° . Similarly, during this interval, the *Switch1* feeds the *Startup Reactive Current Command* at the output. When the *Lookup Table Enable Time* input goes high, it denotes that the *Lookup Table* is enabled. This makes the *Switch2* select the firing angle from the *Lookup Table*. After the *Lookup Table* is enabled, *Switch1* selects the *Reactive Current Command* signal from the *Reactive Current Command System* which has a rate limiter built into it. The introduction of this extra rate limiting assures that the *Reactive Current Command* is not altered instantaneously which might introduce large transients in the system. This is the precautionary measure taken to ensure the inputs of the controller are quasistatic or slowly varying compared to the response speed of the overall compensator system.

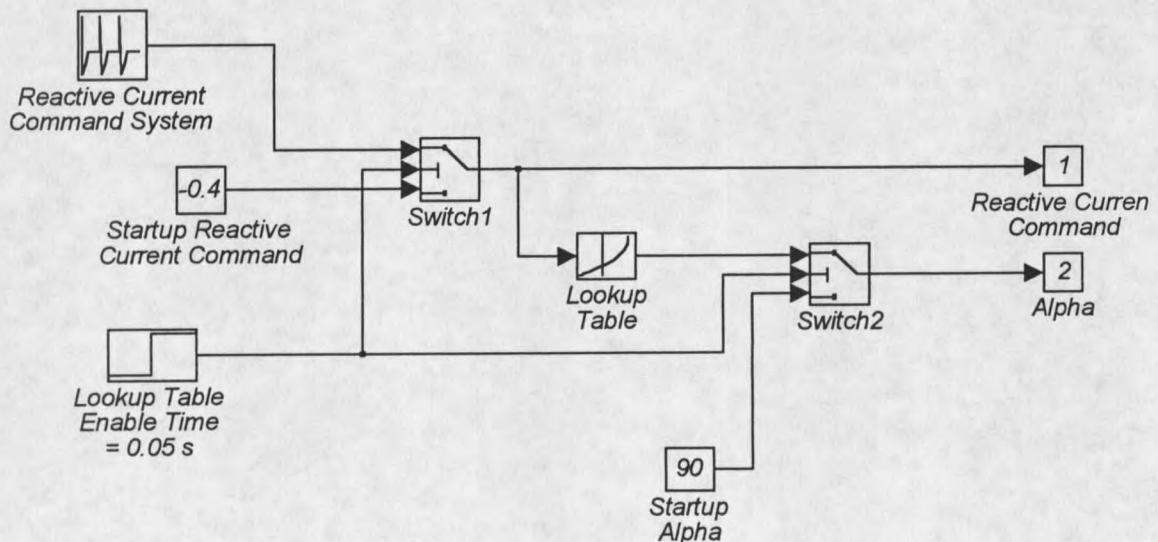


Figure 41. Model to simulate the lookup table enabling algorithm.

The model described in this chapter is used to simulate the hybrid reactive compensator system with various control strategies. The simulation is performed in the MATLAB-Simulink software. The results obtained from these simulations are presented in the following chapter.

CHAPTER 6

SIMULATION AND EXPERIMENTAL RESULTS

Introduction

As presented in the previous chapter, the proposed hybrid static reactive power compensator is modelled in MATLAB-Simulink software. This chapter presents the results of the simulations done on this model. The simulation model is designed for 40% compensation, both in lagging and leading modes. The utility line voltage is assumed to be as 1 per unit. Hence the magnitude of the injected reactive current varies within 0.4 per unit with lagging and leading power factors. The simulations will demonstrate that the system operates as desired throughout the dynamic range, thus confirming the feasibility of the approach as presented in this thesis. The subsequent sections include the simulation results for various transient and steady state cases, both in lagging and leading compensation zones. A particularly interesting transient case when the system passes through the resonance zone is also included in these results. Finally, the simulation results of the operation near the full capacity leading compensation wherein the system fails to obtain a periodic steady state operating point are appended.

A critical point in governing the stability of the system is the performance of the firing angle generator. It may be seen that without the correct firing angle information, and

a certain amount of current being forced into it, the SVC voltage may increase beyond limits or decrease to zero. The firing angle generator as developed in this work is entirely based on the static transfer characteristics as derived in the appendix. The validity of the transfer characteristics is confirmed by using laboratory experiments. The concluding section of this chapter presents the experimental results.

Start-up Characteristics

As mentioned in the previous chapters, the dynamic properties of a current controlled SVC are highly non-linear and complex. Preliminary investigations have shown that the starting transients often end up causing large transients in the SVC voltage. This is due to the fact that the SVC capacitor is discharged at the start-up condition. If current is forced into the capacitor in discharged condition, it is probable that the voltage across it may exhibit unnecessary transients. So, in order to avert any such undesired transients, a start-up procedure is devised which allows a precharging interval for the SVC capacitors. The capacitor charging is carried out directly from the utility line through a charging resistor (Figure 30). Hence during this interval, the voltage across the capacitors is tied to the utility line, while the current exhibits a transient behavior.

Figures 42 and 43 show the charging voltage and the charging current of the capacitor of a single phase. The precharging interval is of 0.025 seconds. It may be seen that the voltage across the capacitors during this interval is equal to 1 per unit. After the precharging interval, the charging resistor is shorted, and the power source is switched to

the reactive current injector. Hence one may observe a small glitch in the current in Figure 43 at 0.025 seconds. This also causes a slight transient in the capacitor voltage which is seen in Figure 42.

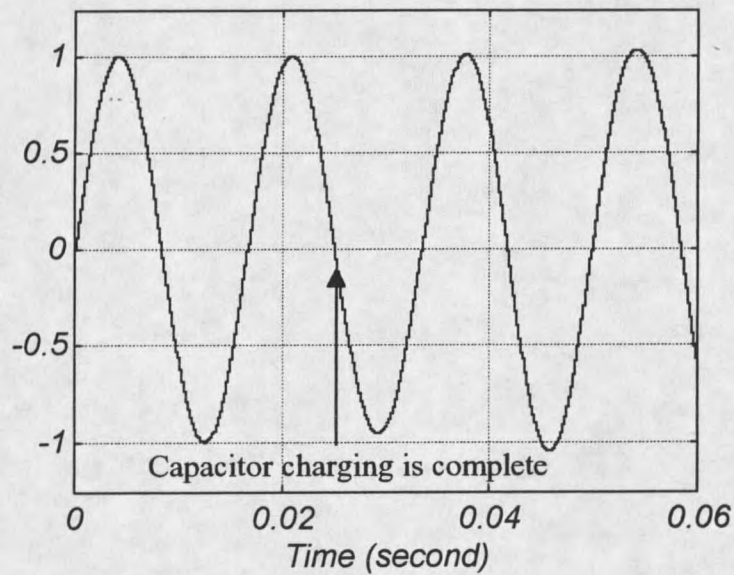


Figure 42. SVC capacitor voltage during the precharging interval.

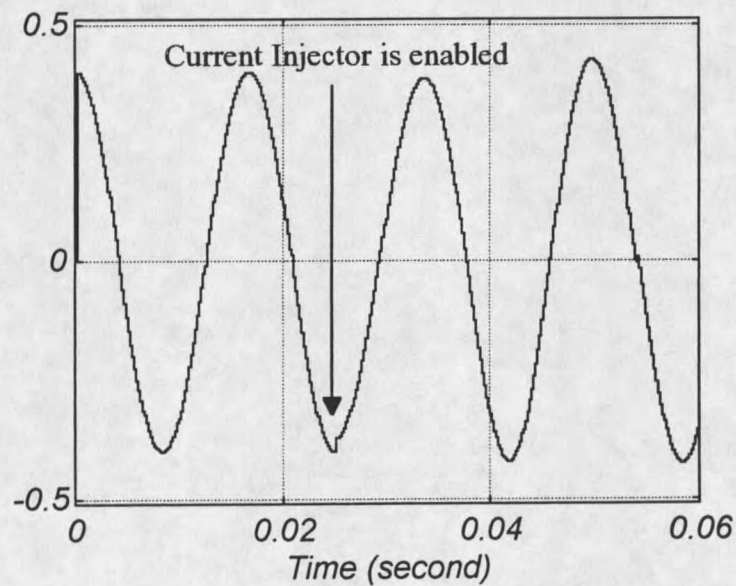


Figure 43. SVC capacitor current during the precharging interval.

The firing angle of the thyristors is fixed at 90° during this start-up procedure. This results in having the inductors fully in the TCR circuit. The reactive current command is accordingly set at full lagging capacity i.e. at 0.4 per unit lagging during this interval.

Dynamic Performance in the Lagging Compensation Zone

After the system settles through the start-up algorithm, the system is delivering lagging compensation at its full capacity owing to the reactive current command of 0.4 per unit lagging. Next the reactive current command is slowly ramped up to the desired compensation level. This is illustrated in Figure 44. The slow ramping of the reactive current command causes the magnitude of the injected reactive current to fall at the same rate. This may be seen in Figure 45.

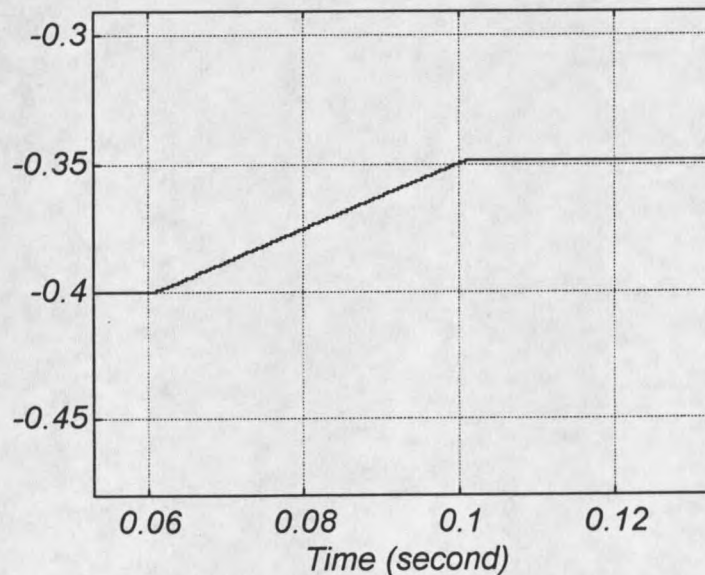


Figure 44. Transient in the reactive current command in the lagging compensation zone.

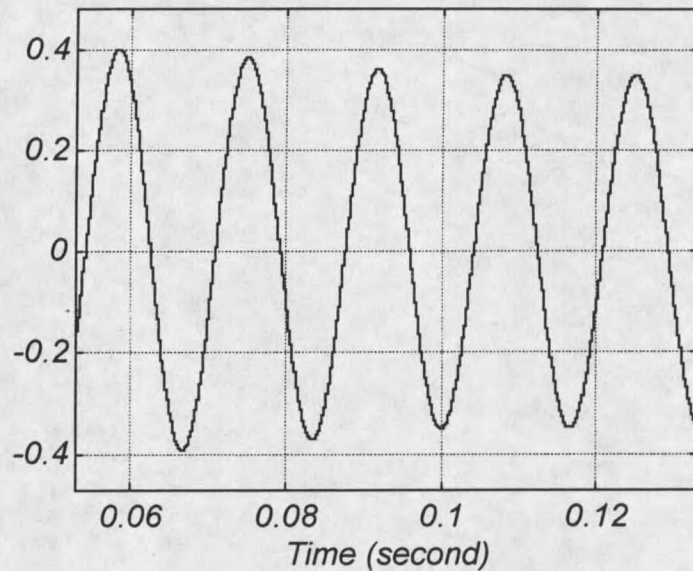


Figure 45. Transient in the reactive current in the lagging compensation zone.

Corresponding to the reactive current command, the firing angle generator issues the corresponding firing angle α to the SVC during this process. Figure 46 illustrates the ramping up of the firing angle in response to the reactive current command.

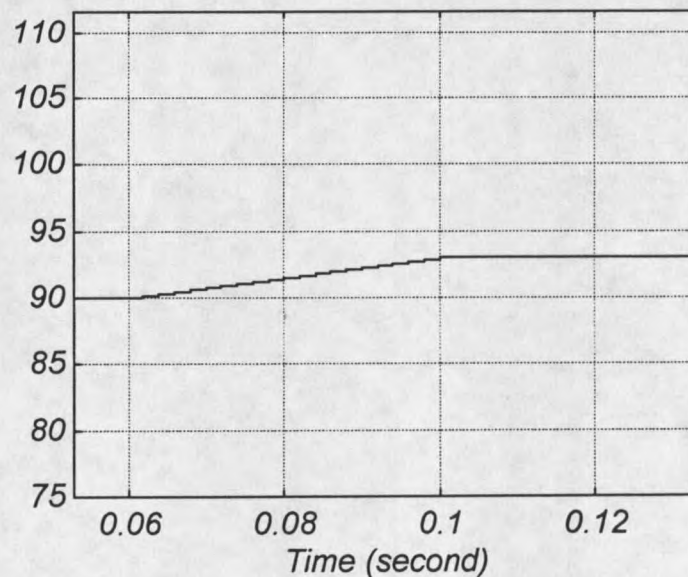


Figure 46. Transient in the firing angle in the lagging compensation zone.

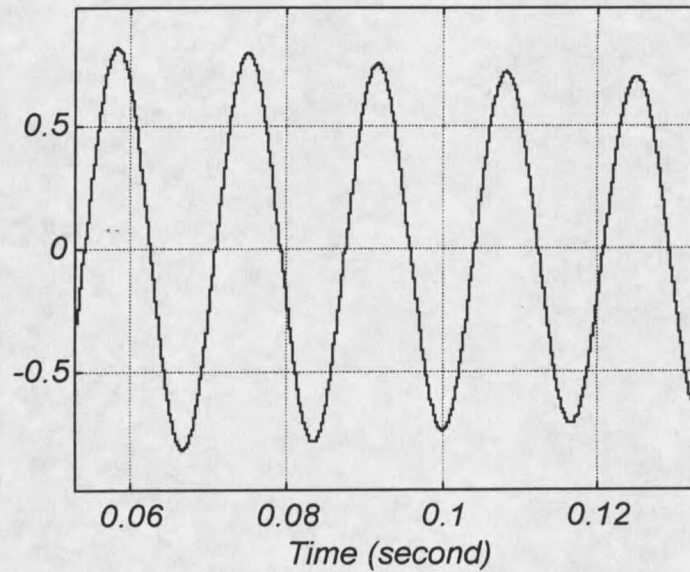


Figure 47. Transient in the TCR current in the lagging compensation zone.

With the change in the firing angle the equivalent inductance in the TCR changes. This changes its effective impedance and so also the current flowing through it. This is depicted in the Figure 47.

As the system is current controlled, and the current through the TCR changes, the current in the shunt capacitor also changes. This produces an effect of changing the capacitor voltage slightly during the transient as shown in Figure 48.

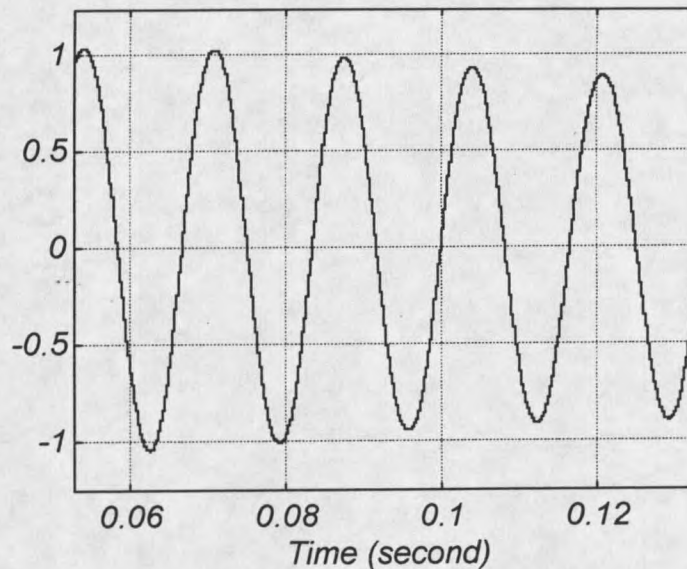


Figure 48. Transient in the SVC voltage in the lagging compensation zone.

Ideally, the SVC voltage (which is also the same as capacitor voltage) should always be controlled at utility line voltage i.e. at 1 per unit. If this is satisfied, then the voltage drop across the current source is negligible and thus reduces the stress on it considerably. But when the operating point is changed, this voltage is seen to be slightly collapsing during the transient in Figure 48. This may be because of the static and transient errors in the lookup table.

Steady State Performance in the Lagging Compensation Zone

This section presents the results obtained in the steady state for the lagging compensation. An operating point to supply about 23% lagging compensation is selected. The system is started as usual, with the capacitor precharging interval. At the end of the

start-up procedure, the compensator is supplying its full capacity lagging compensation i.e. 40% or a lagging current of -0.4 per unit. After the system settles through the start-up procedure, the reactive current command is slowly ramped and reaches 23% or -0.2373 per unit as shown in Figure 49.

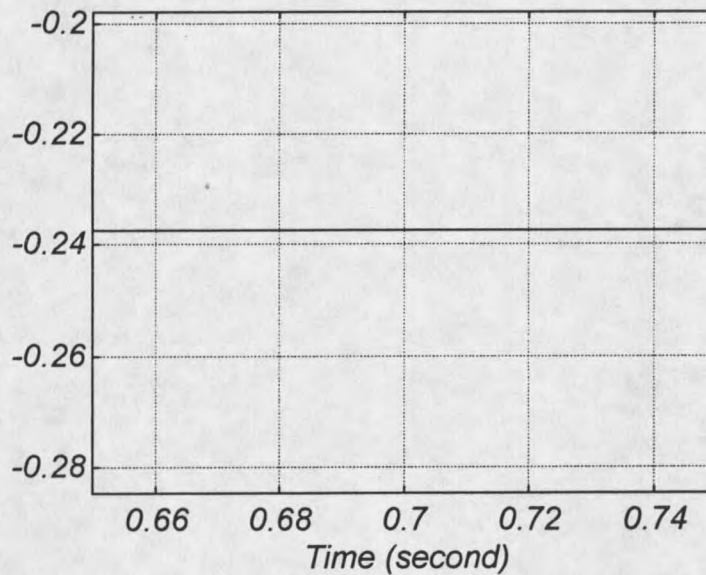


Figure 49. Steady state reactive current command in the lagging compensation zone.

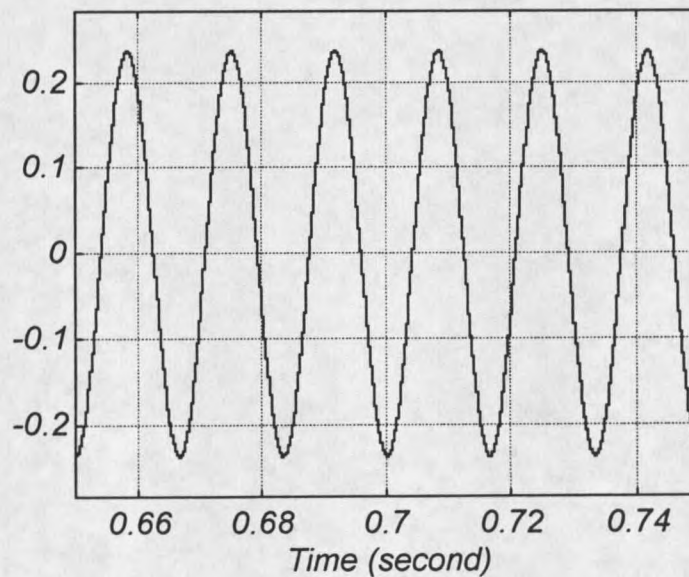


Figure 50. Steady state reactive current in the lagging compensation zone.

The firing angle generator computes the corresponding firing angle from the lookup table. This α is required to obtain 1 per unit voltage from the SVC, given a current of 0.23 per unit. The firing angle is seen to have tracked the reactive current command through the transient and has settled at 100° in Figure 51.

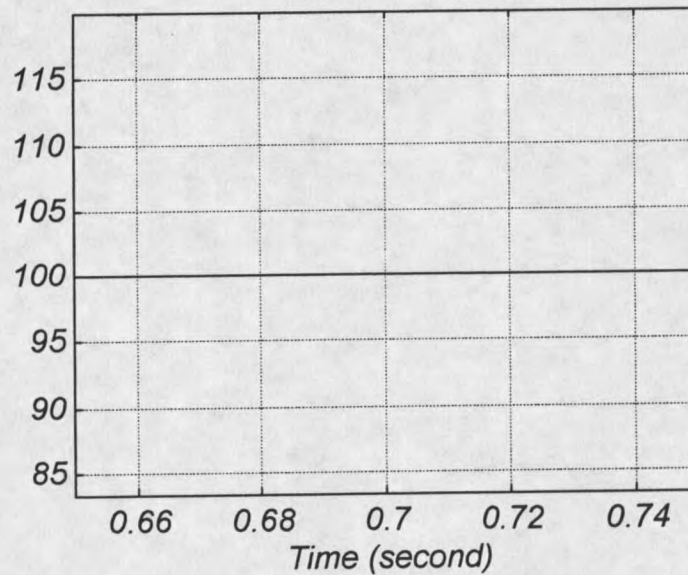


Figure 51. Steady state firing angle in the lagging compensation zone.

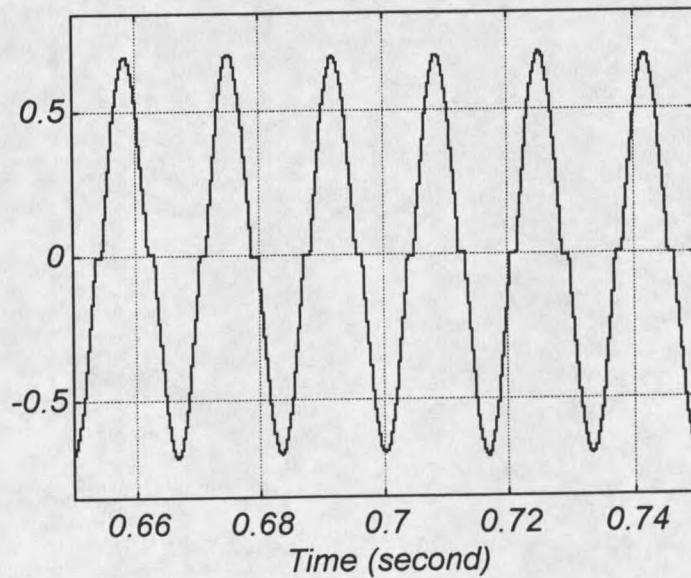


Figure 52. Steady state TCR current in the lagging compensation zone.

The equivalent impedance of the TCR changes with the variation in firing angle, and so does change the TCR current. Figure 52 illustrates the steady state TCR current for the 23% lagging compensation.

Finally, Figure 53 show the SVC voltage for this particular case. It may be observed that the SVC voltage is about 95% of its desired value, and may be considered as satisfactory. The difference in the desired value of 1 per unit and the actual value as seen in this figure may be coming because of the harmonic interaction of the current injected SVC which incorporates thyristor firing. As can be seen from the appendix, the relation between the firing angle and the impedance of the current fed SVC is derived using only the fundamental components of voltage and current. But the actual voltage also includes the harmonic content owing to the thyristor switching. This may lead to residual errors in the firing angle generator which are shown up in the SVC voltage.

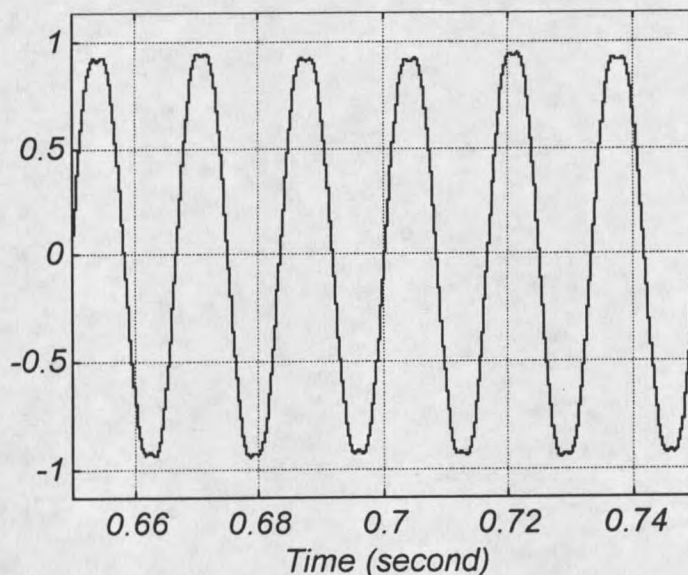


Figure 53. Steady state SVC voltage in the lagging compensation zone.

Dynamic Performance in the Resonance Zone

To mitigate the needs of the reactive power supply, the hybrid compensator should be capable of leading compensation. But due to the problem of the stability in the start-up dynamics, the system was started as a lagging compensator. Now in order to be able to supply the leading power factor current, the system needs to go through the resonance.

Reference [7] addresses the issue of the resonance in the SVC networks. It is concluded that the operation near the resonance zone is not reliable in terms of the stability. The system exhibits extremely non-linear performance which is very difficult to predict and analyze. The following figures present the results of the hybrid compensator system operation as the reactive current command goes from lagging to leading compensation zone, in other words through the resonance point.

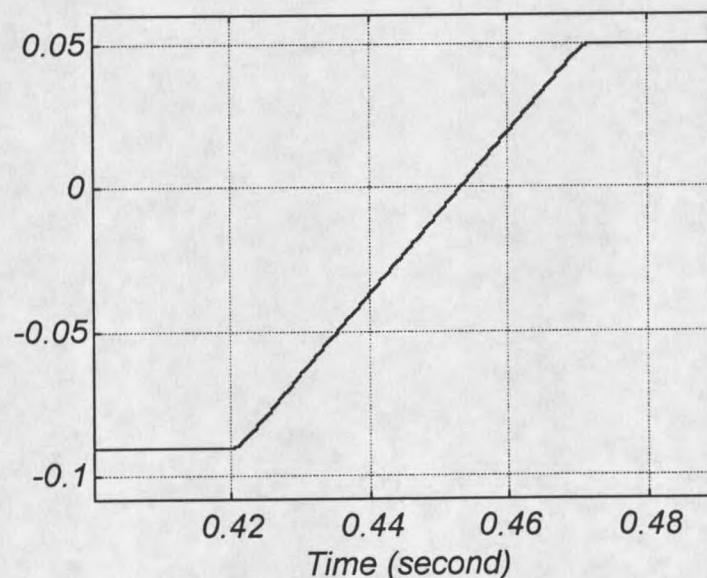


Figure 54. Transient in the reactive current command in the resonance zone.

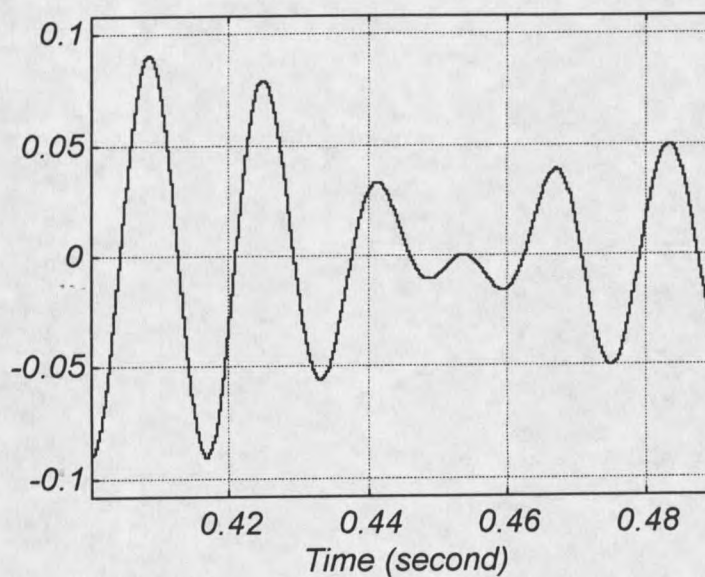


Figure 55. Transient in the reactive current in the resonance zone.
The current is seen to be reversing the phase.

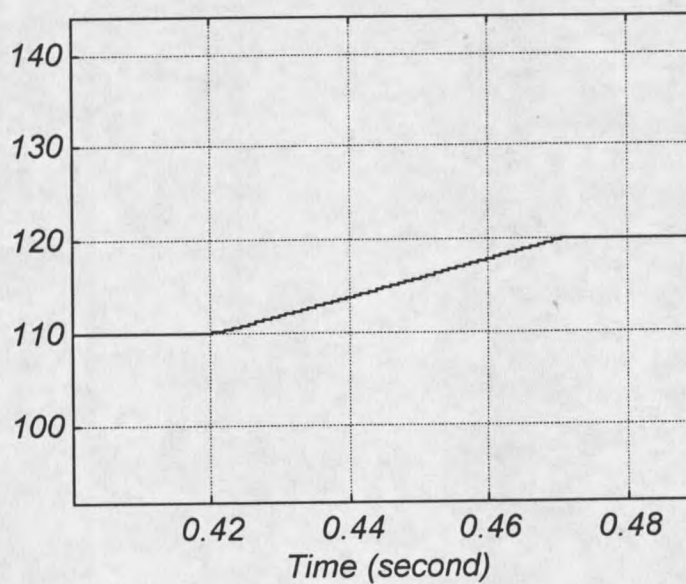


Figure 56. Transient in the firing angle in the resonance zone.

Corresponding to the reactive current command as shown in Figure 54, the injected reactive current reverses the phase after going through the null point. This may be seen in Figure 55. Figure 56 shows the firing angle variation which corresponds with the reactive current command.

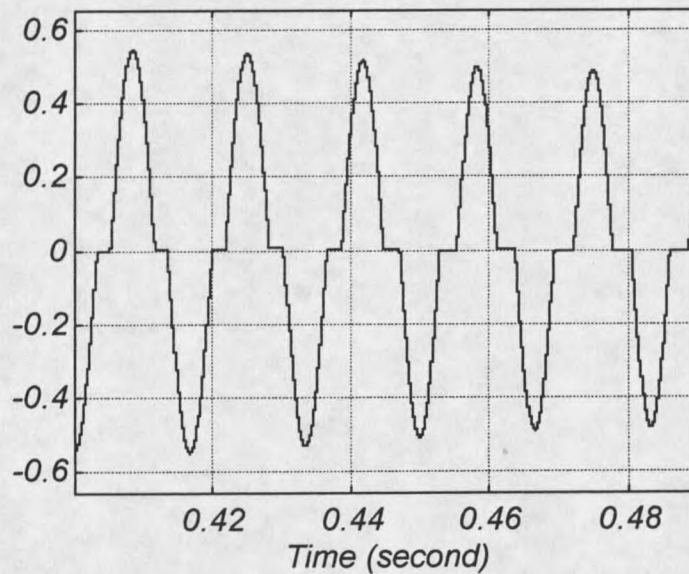


Figure 57. Transient in the TCR current in the resonance zone.

As the firing angle changes, the equivalent impedance of the SVC changes causing a transient in the TCR current as illustrated in Figure 57.

The problem of resonance in this particular case of hybrid compensator is that the reactive current injected in the SVC and the utility system is zero; and yet we need the SVC voltage to be finite (ideally, equal to the utility line voltage). This calls for the SVC impedance to be infinite which is impractical and can only be attained by having a parallel

resonance of the TCR and the capacitor. It may be observed that one can never realize a steady state operating point in this zone, since the equilibrium is unstable. The present quest is just to confirm whether the proposed system can proceed through the resonance point without inducing large transients. And it proves from the Figures 57-58 that the system can safely pass through the resonance without any noticeable untoward results in TCR currents or SVC voltages.

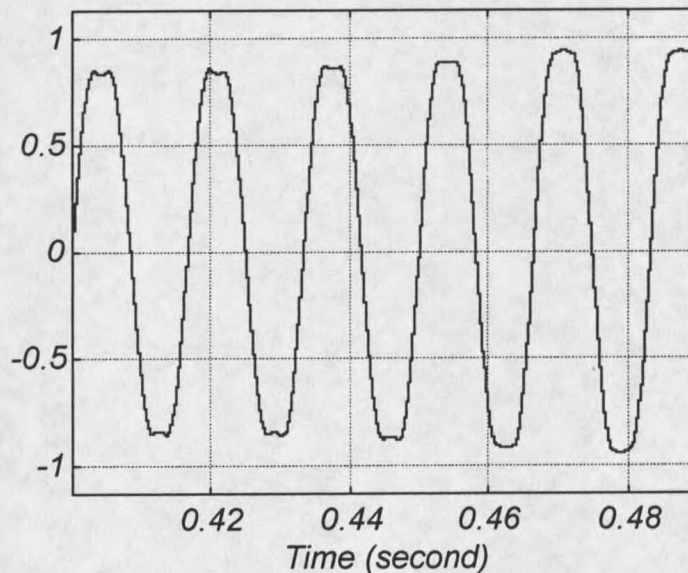


Figure 58. Transient in the SVC voltage in the resonance zone.

As seen in Figure 58, the SVC voltage is rich in harmonic content with the peaks flattened out. So also, the magnitude is less than the ideal i.e. 1 per unit. However, there is no misfiring of thyristors in this interval, which preserves the normal operation of the system through the resonance zone.

Dynamic Performance in the Leading Compensation Zone

After the system passes through the resonance zone, it starts supplying leading compensation. The reactive current command is again slowly ramped up to the desired compensation level. This is illustrated in Figure 59. The slow ramping of the reactive current command causes the magnitude of the injected reactive current to rise at the same rate. This may be seen in Figure 60.

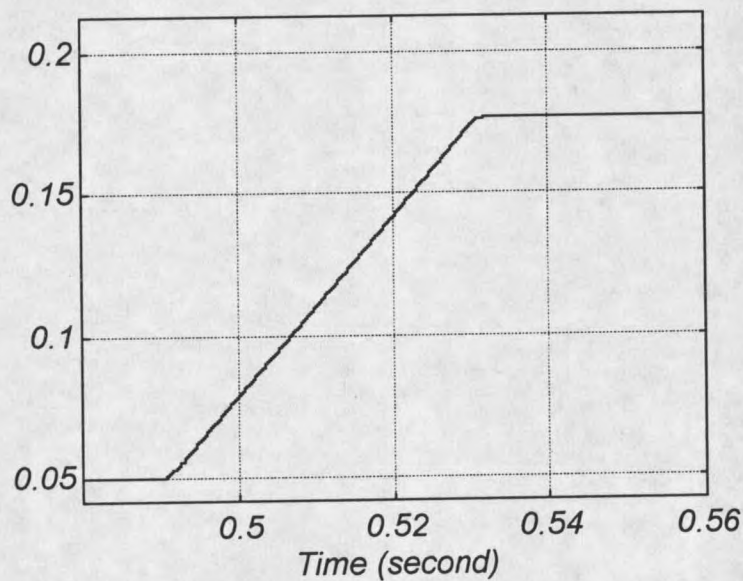


Figure 59. Transient in the reactive current command in the leading compensation zone.

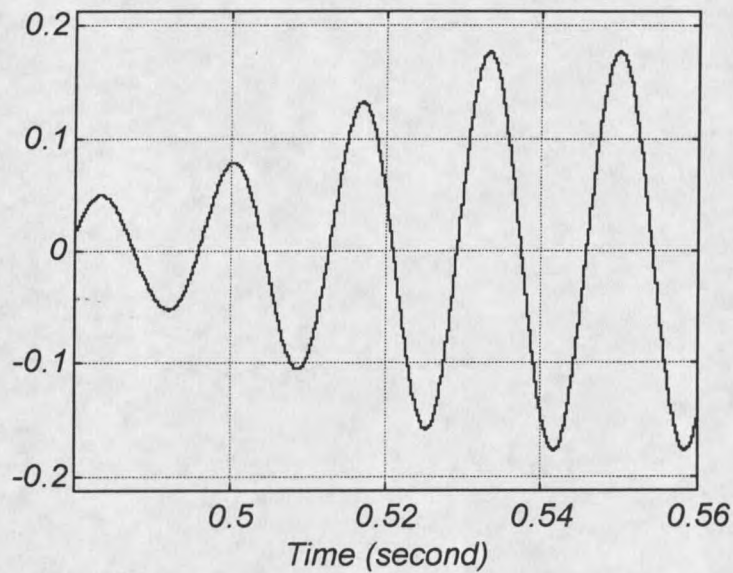


Figure 60. Transient in the reactive current in the leading compensation zone.

Corresponding to the reactive current command, the firing angle generator issues the corresponding firing angle α to the SVC during this process. Figure 61 illustrates the ramping up of the firing angle in response to the reactive current command.

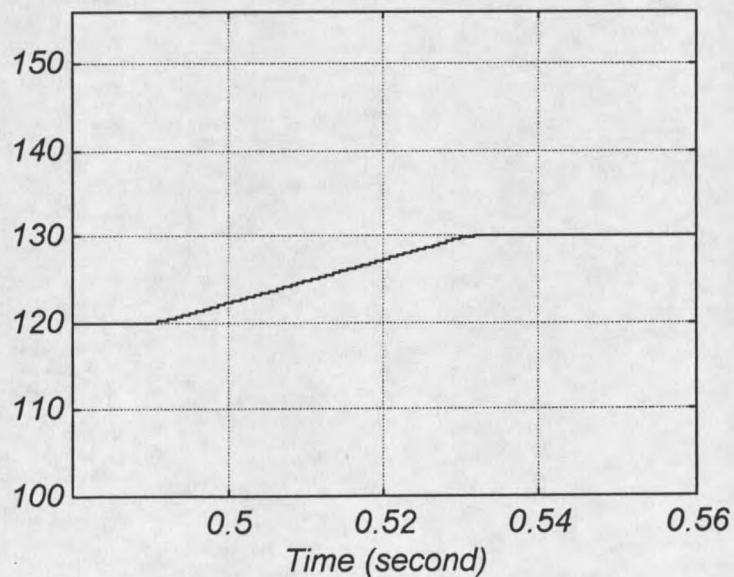


Figure 61. Transient in the firing angle in the leading compensation zone.

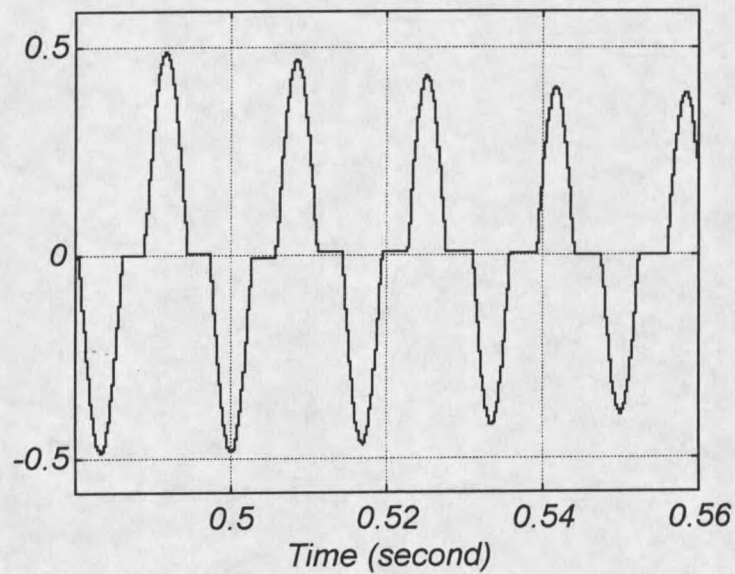


Figure 62. Transient in the TCR current in the leading compensation zone.

With the change in the firing angle the equivalent inductance in the TCR changes. This changes its effective impedance and is reflected in the current flowing through it as illustrated in the Figure 62. The effect of changing the capacitor voltage slightly during the transient as shown in Figure 63.

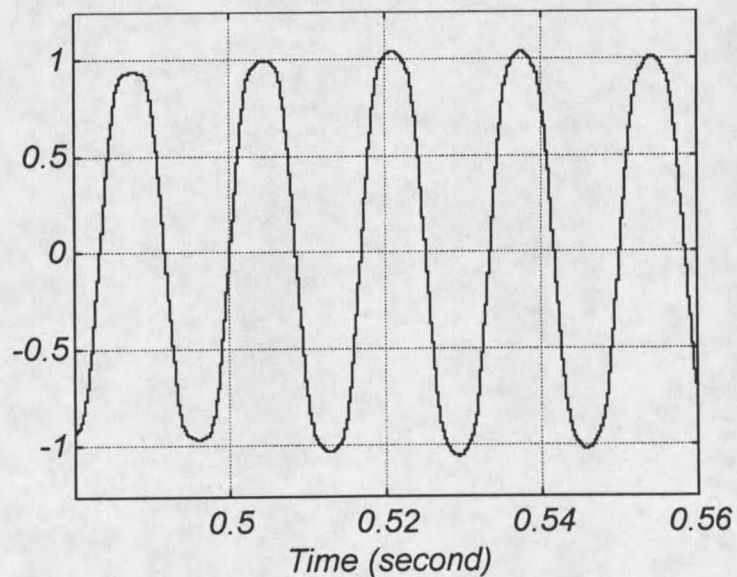


Figure 63. Transient in the SVC voltage in the leading compensation zone.

When the operating point is changed in the leading compensation zone, this voltage is seen to be slightly increasing in the transient in Figure 63. This is opposite to what had happened in the lagging compensation zone in a similar set of conditions (Figure 48).

Steady State Performance in the Leading Compensation Zone

This section presents the results obtained in the steady state for the leading compensation. An operating point to supply about 17% leading compensation is selected. The system is started as usual, with the capacitor precharging interval. After the start-up procedure, the reactive current command is slowly ramped up and carried all the way across the resonance in the leading compensation zone. Figure 64 shows that the reactive current command is settled at around 17% or to 0.1770 per unit.

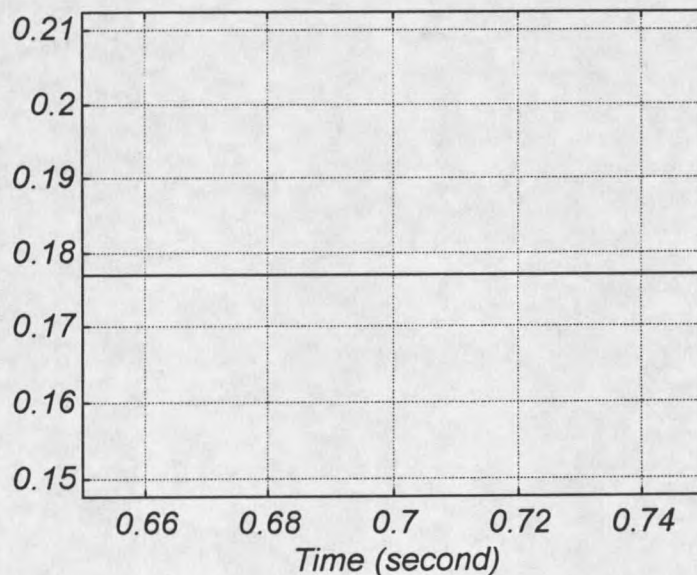


Figure 64. Steady state reactive current command in the leading compensation zone.

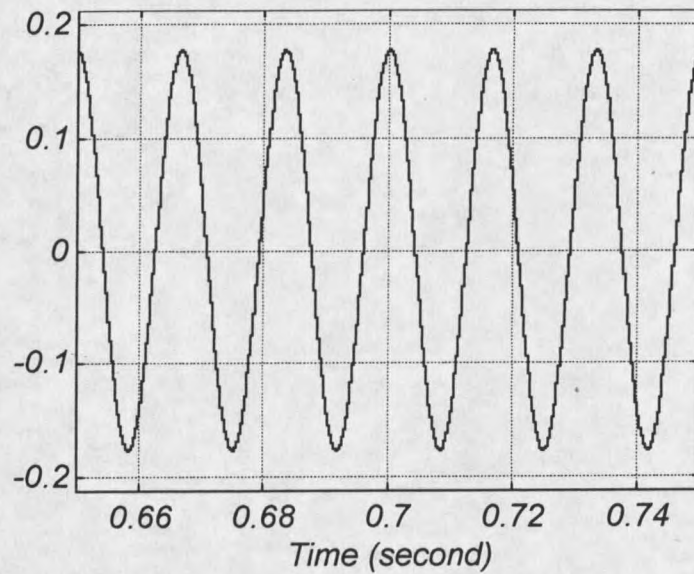


Figure 65. Steady state reactive current in the leading compensation zone.

The firing angle generator computes the corresponding firing angle from the lookup table. This α is required to obtain 1 per unit voltage from the SVC, given a current of 0.17 per unit. The firing angle is seen to have tracked the reactive current command through the transient and then settled at 130° in Figure 66.

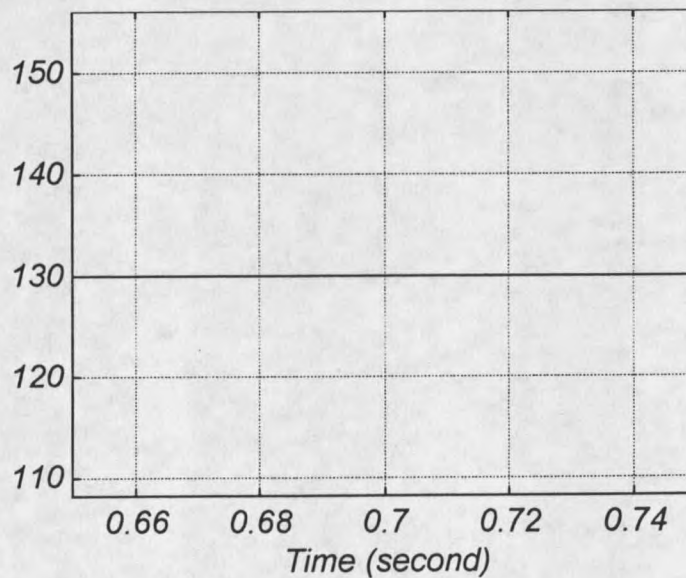


Figure 66. Steady state firing angle in the leading compensation zone.

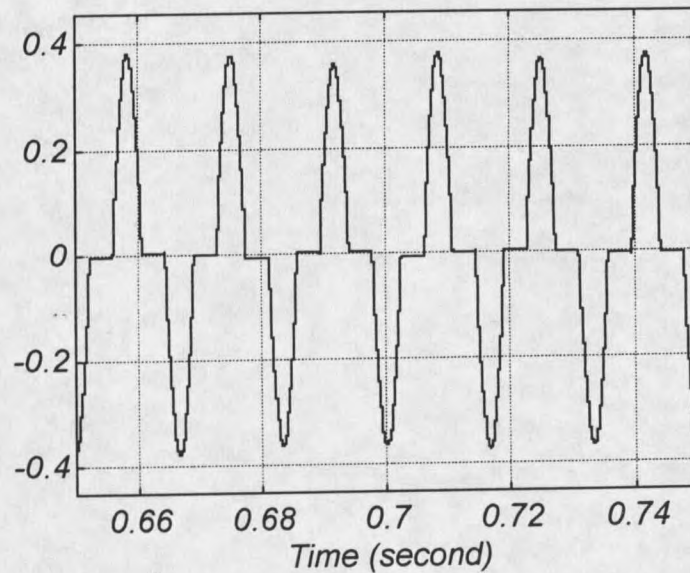


Figure 67. Steady state TCR current in the leading compensation zone.

The equivalent impedance of the TCR changes with the variation in firing angle, and so does change the TCR current. Figure 67 illustrates the steady state TCR current for the 17% leading compensation. Finally, Figure 68 shows the SVC voltage which is almost equal to its desired value for this particular case.

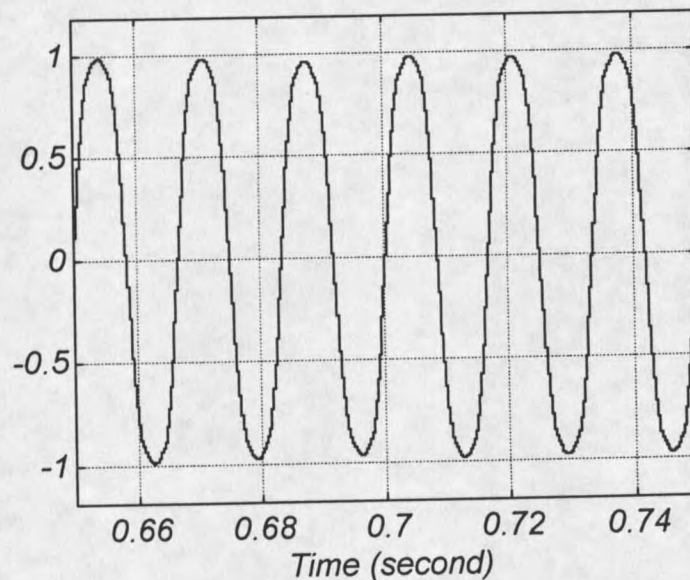


Figure 68. Steady state SVC voltage in the leading compensation zone.

Performance Near Full Capacity Leading Compensation

It is derived in Chapter 4 (Stability Analysis) that the system under investigation fails to attain a periodic steady state operating point when operated at its full capacity in the leading compensation zone. The following figures demonstrate the operation of the hybrid compensator near its full capacity leading compensation. The operating point to supply about 28% leading compensation is selected. It may be noticed that the system is designed to supply a maximum of 40% compensation. Figure 69 illustrates the reactive current command being ramped up till about 28% or 0.28 per unit. Figure 70 shows the injected reactive current following the reactive current command.

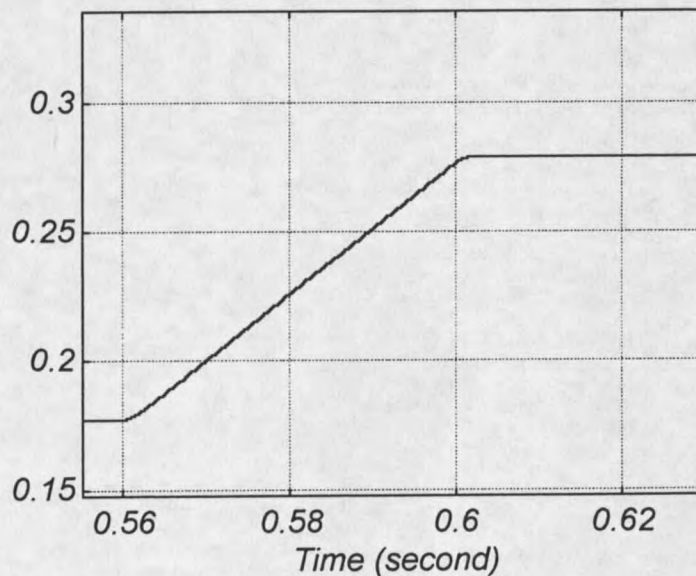


Figure 69. Reactive current command near full capacity leading compensation point.

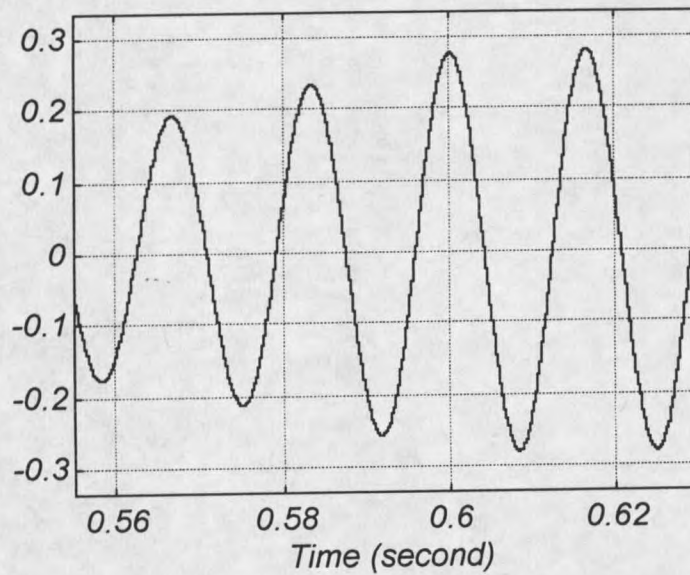


Figure 70. Reactive current near full capacity leading compensation point.

Figure 71 shows the corresponding change in the firing angle generated by the firing angle generator which uses the reactive current command as the reference.

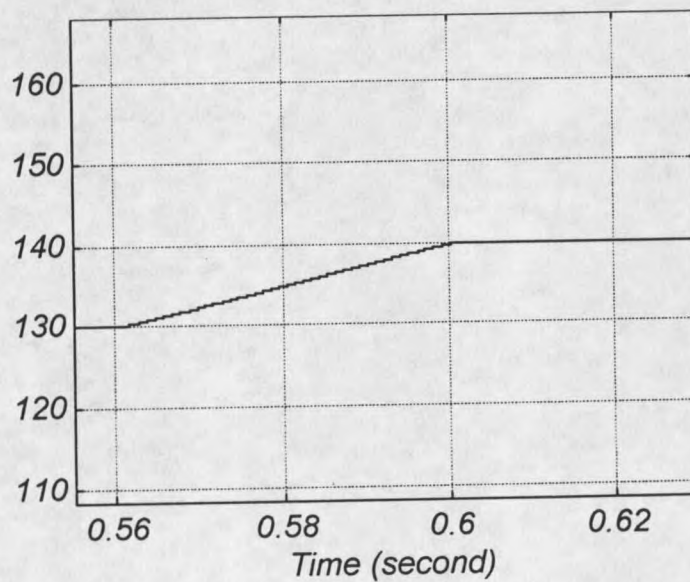


Figure 71. Firing angle near full capacity leading compensation point.

Figure 72 illustrates the TCR current. As is evident from this figure, the thyristors start misfiring at about 0.59 seconds. As the thyristor switches remain open when they are supposed to be closed, the current drawn by the TCR is zero during that interval. As this is a current regulated system, the injected current forces itself into the shunt connected capacitor of the SVC. This leads to a big transient in the SVC voltage (which is same as the capacitor voltage). This voltage is also impressed against the TCR. In the next cycle, when the thyristors are fired again, the inductor in the TCR sees this big transient voltage, and produces a big transient in the current. This leads to the eventual losing of the periodic state operating point.

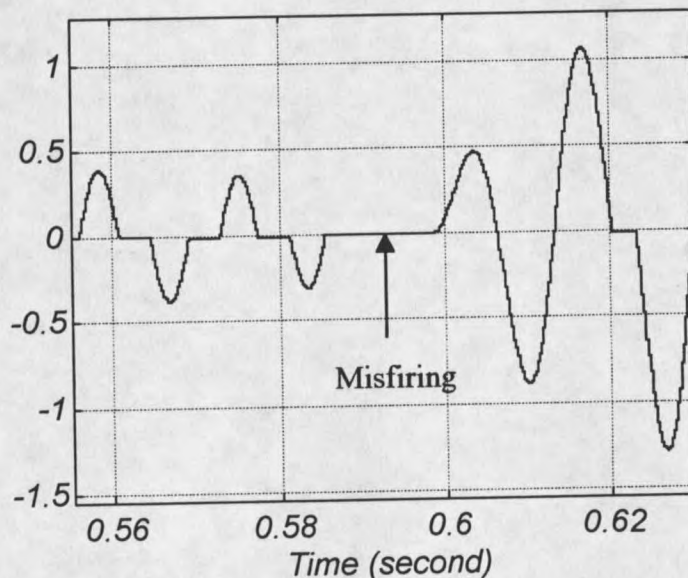


Figure 72. TCR current near full capacity leading compensation point.

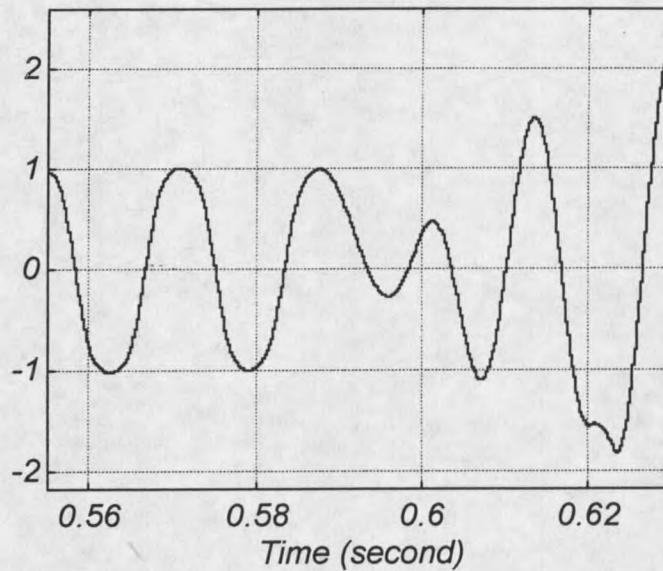


Figure 73. SVC voltage near full capacity leading compensation point.

The SVC voltage is seen to be losing the periodic steady state after the thyristors misfire in Figure 73. This confirms the analysis results of Chapter 4 that the system operation is unpredictable and may lead to the loss of the periodic steady state as the compensator gets closer to operating point which delivers the full capacity leading compensation.

Experimental Results

The proposed hybrid reactive power compensator is a combination of a power electronic current injector and a series connected thyristor based SVC. The SVC acts as a variable reactance and is employed to provide a voltage bias such that the voltage stress

across the power electronic current injector is minimal for any given current. So it is evident that the feasibility of this approach depends mainly on the performance of the SVC in developing the required fixed voltage (ideally, equal to the utility line voltage) for any given value of the injected current. This is accomplished by varying the effective impedance of the SVC by firing angle control. Thus it becomes clear that the firing angle generator is the heart of the system; and is the most critical element in ensuring a desired performance. The firing angle generator is based on the static transfer characteristics between the firing angle and the effective reactance of the current fed SVC as derived in the appendix. The validity of the transfer characteristics is verified by some laboratory experiments. Figure 74 illustrates the circuit schematic of the experimental setup.

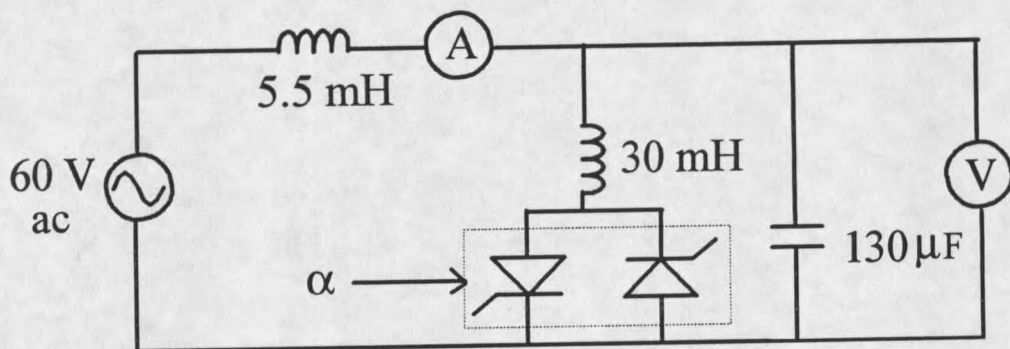


Figure 74. Circuit schematic of the experimental setup.

As shown in Figure 74, a prototype model of a SVC is tested in the laboratory. The values of the capacitance and inductance used in the SVC are $130\mu\text{F}$ and 30 mH respectively. The TCR current is controlled by controlling the firing angle (α) of the thyristors which in effect controls the conduction angle (σ). A 60 V ac supply derived

from the single phase mains acts as a power source. The line current is regulated by the 5.5 mH inductance. The voltmeter and ammeter are connected as shown in the figure which measure the fundamental voltage across the SVC and the fundamental current injected into it. The fundamental reactance is then found by dividing the voltage by the current. The following table (Table 2) summarizes the values obtained for the fundamental reactance by this experiment and by the formula as derived in the appendix. The corresponding values are plotted in Figure 75.

Table 2. Comparison of the experimental and calculation results.

Firing Angle (Degrees)	Fundamental Reactance From Experiment (Ohms)	Fundamental Reactance From Calculations (Ohms)
90.9	-27	-26.6
93.49	-31.4	-30.5
98.46	-44.5	-41.8
102.46	-76.9	-58.4
108.18	-194	130
114.55	61.98	408.7
122.44	37.23	69.21
128.05	31.8	45.05
134.64	28.15	32.91
141.34	25.67	26.95
144.9	24.5	24.96
149.87	22.9	23.08
180	20.55	20.4

Figure 75 illustrates the variation of the experimental and the calculated reactance against the firing angle. As may be seen, the experimental results match fairly accurately with the calculations. This confirms the analytical results and the application of the firing angle generator.

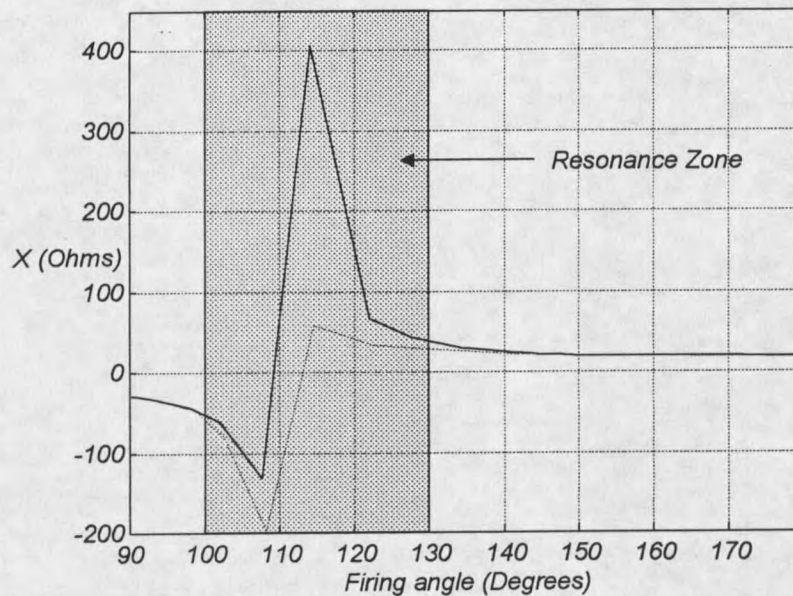


Figure 75. Comparison of the experimental and calculation results for the reactance of the current fed SVC.

The dotted line shows the reactance of the current fed SVC obtained by experiments while the solid line shows the reactance calculated from the formula derived in the appendix. The region where the reactance becomes very big is the region of resonance. The discrepancy in the results in this region may be due to the non-idealities in the current regulation in the laboratory. The other parasitic effects like the resistance of the inductance etc. are also not taken into account in the theoretical results. The following figures illustrate the typical voltage and current waveforms obtained in the experiments.

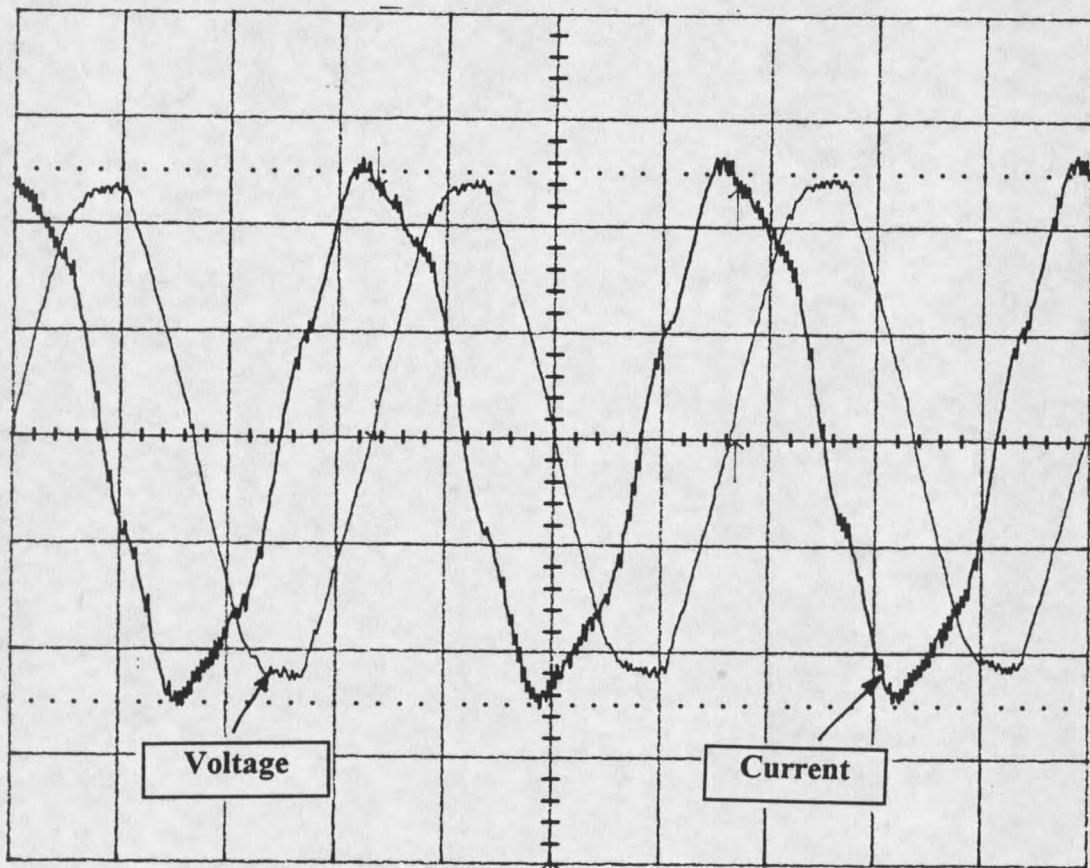


Figure 76. Line voltage and line current in the full capacity leading compensation mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the current is leading the voltage by 90° .

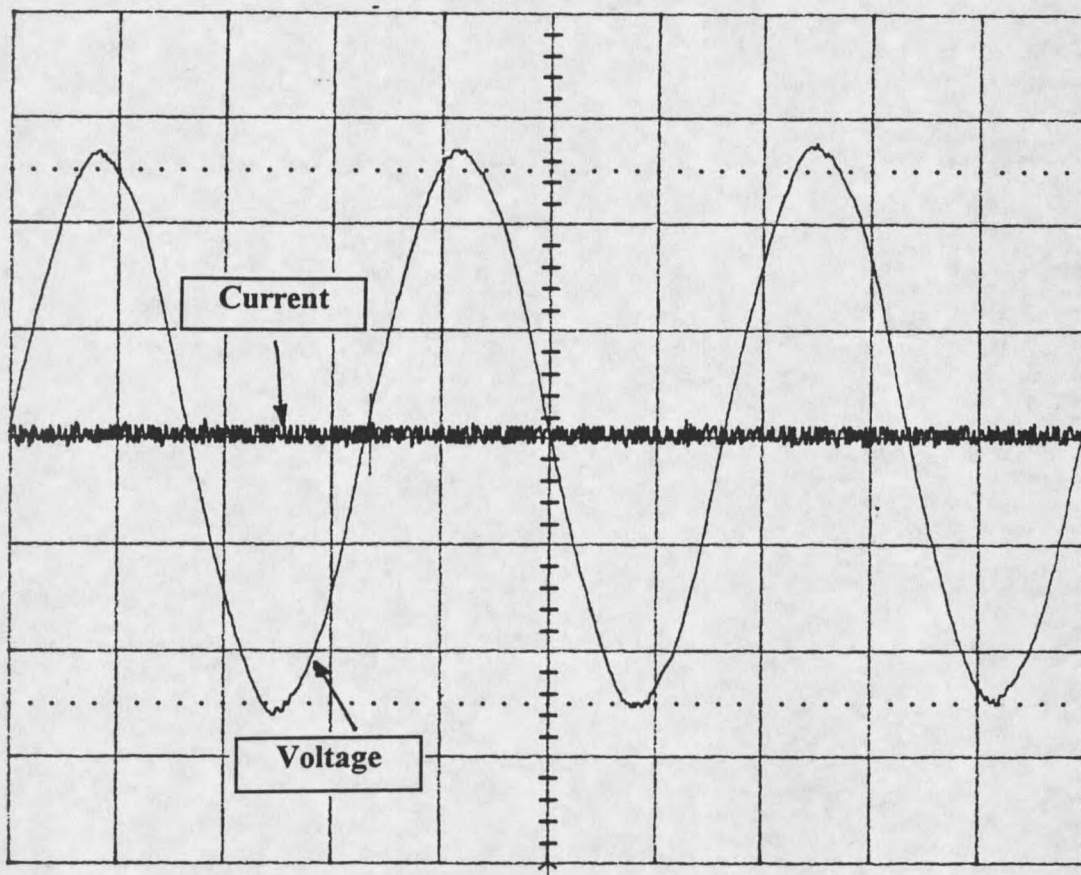


Figure 77. SVC voltage and TCR current in the full capacity leading compensation mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the TCR current is zero, implying the conduction angle is zero, which illustrates that the firing angle of the thyristors is 180° .

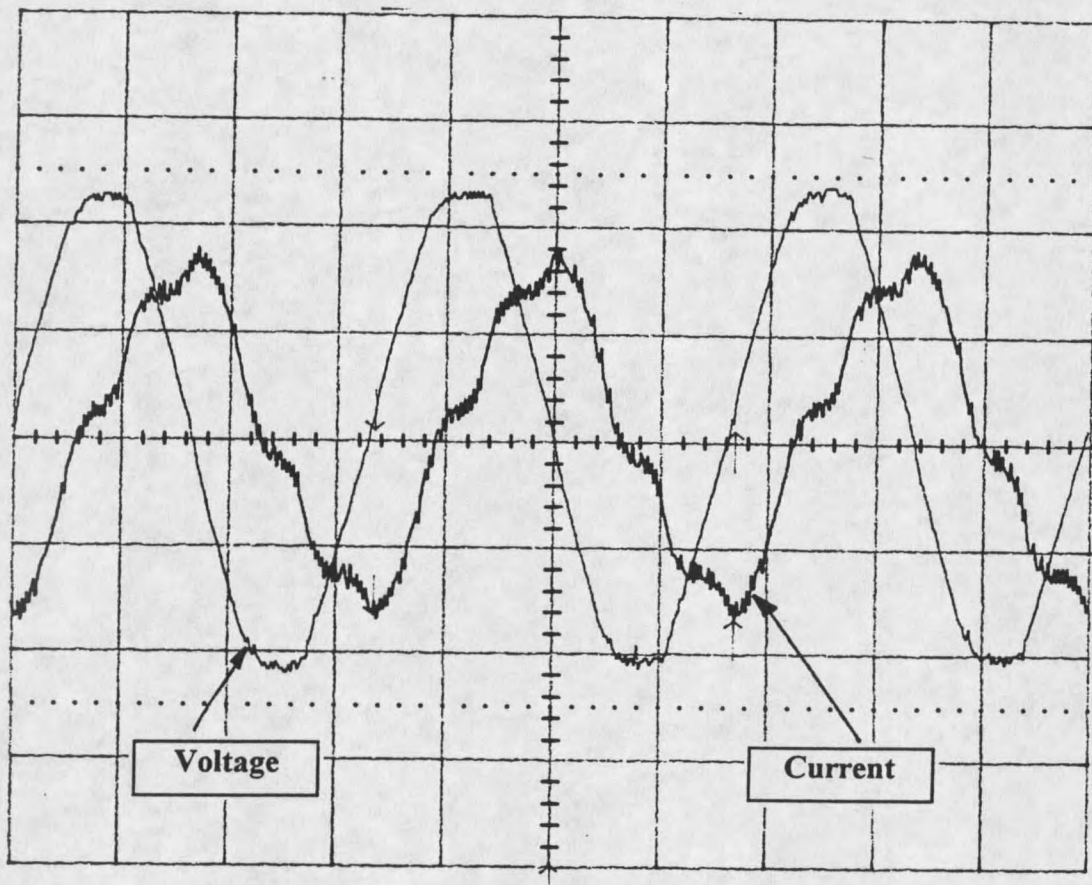


Figure 78. Line voltage and line current in the full capacity lagging compensation mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the current is lagging the voltage by 90° .

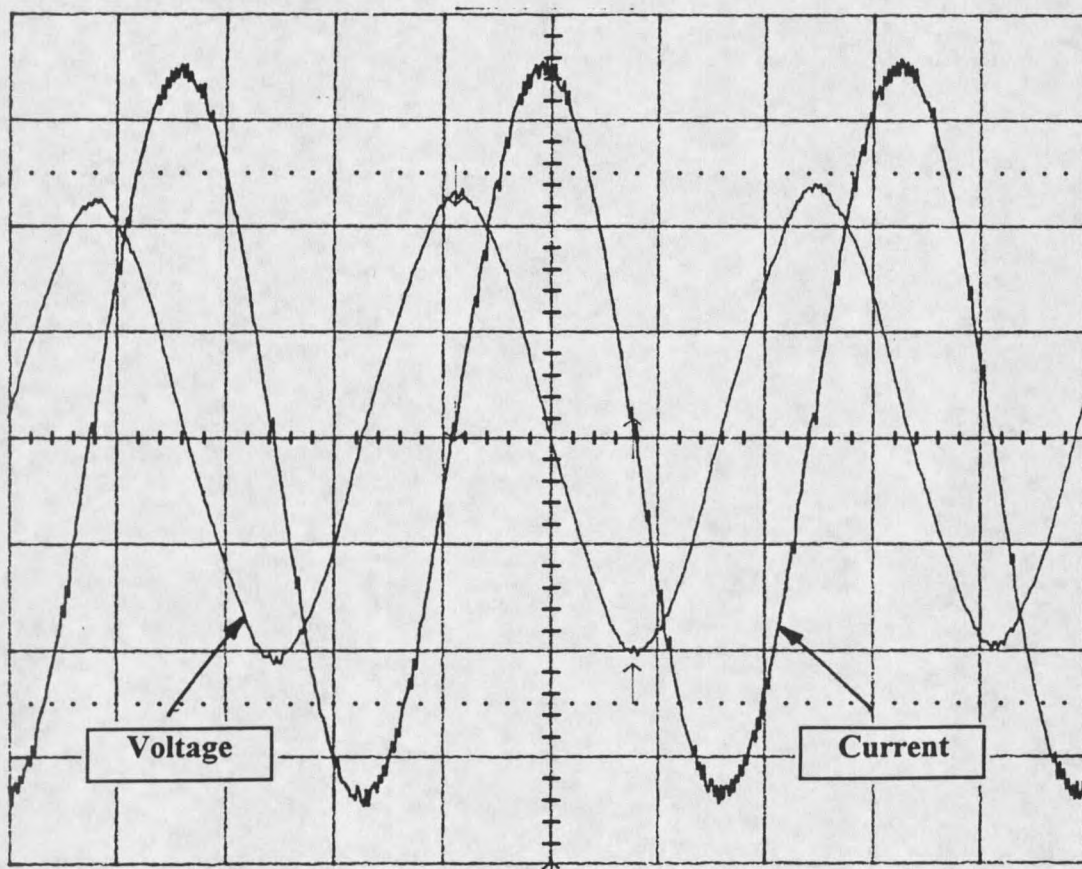


Figure 79. SVC voltage and TCR current in the full capacity lagging compensation mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the TCR current illustrates that the conduction angle is 180° which signifies that the firing angle of the thyristors is 90° .

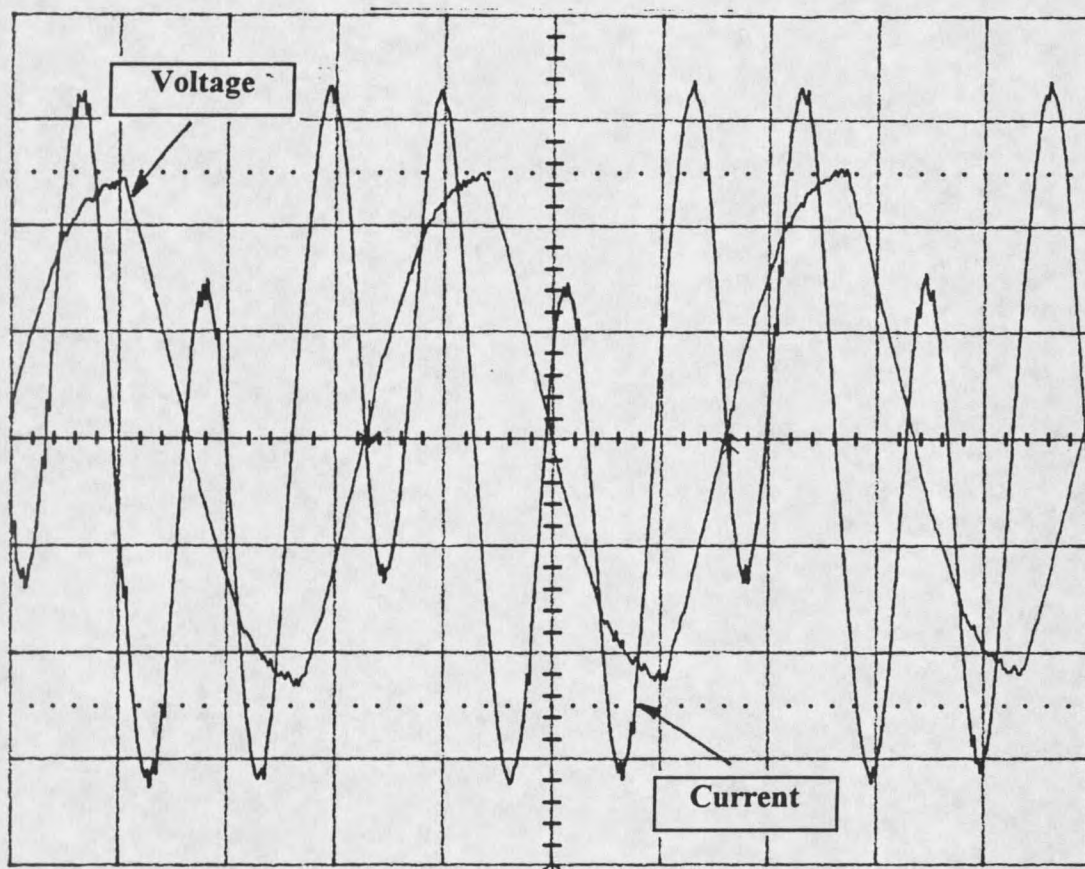


Figure 80. Line voltage and line current in the resonance mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the current waveform is highly distorted in this case as the prototype system is predominantly voltage sourced.

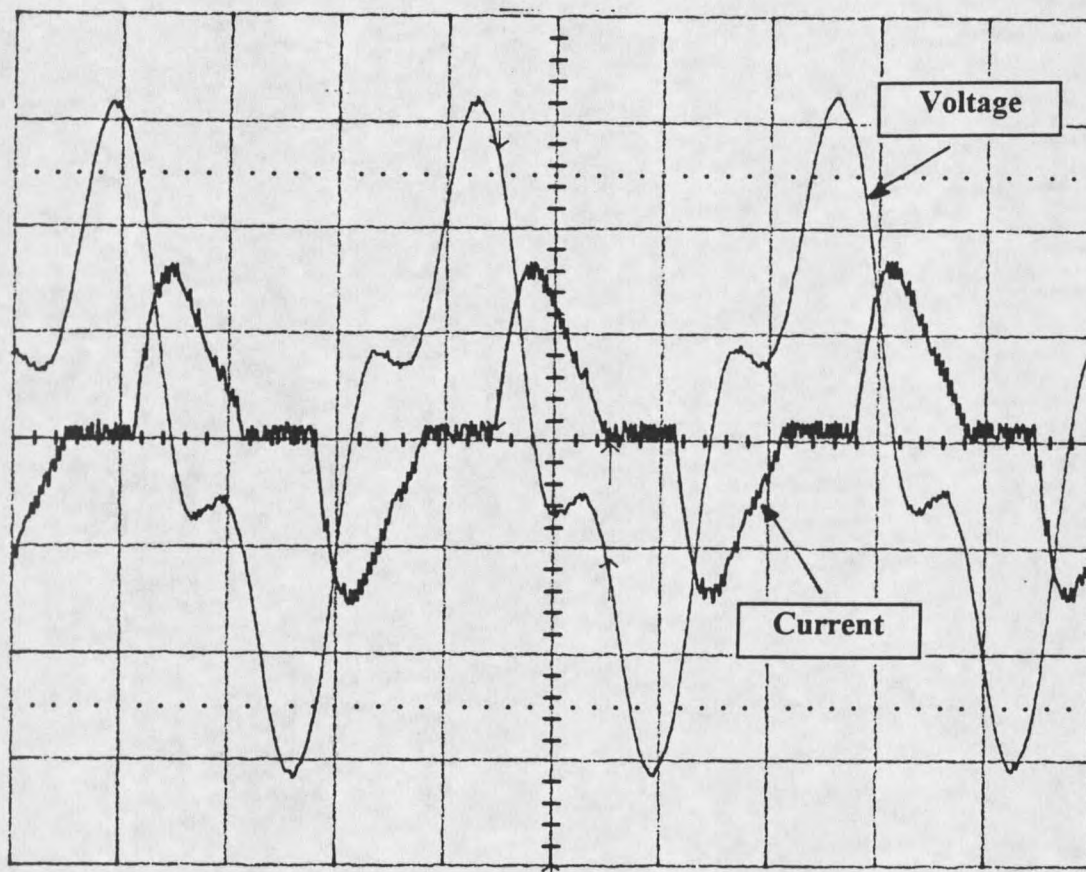


Figure 81. SVC voltage and TCR current in the resonance mode.

Voltage Scale : 40 V/div

Current Scale : 2 A/div

Time Scale : 5 ms/div

It may be observed that the SVC Voltage is distorted when the TCR current is non-zero
i.e. when the thyristors are conducting.

CHAPTER 7

CONCLUSIONS

The principal objective for controlling reactive power flow in power systems is to ensure a flat voltage profile at the load end. Reactive power compensators also serve the purpose of improving the stability limits in power transmission systems.

Present reactive power compensators used for power flow control are generally based on thyristor switched networks. Although they are adequate enough to perform the required control, they have been identified to be bulky, as well as to suffer from harmonic interactions with the utility system. As an alternative approach, numerous topologies using forced commutated power devices have been reported in the literature to overcome these problems associated with the thyristor based equipment. However this approach requires the devices which has the voltage sustaining capability of a typical utility system. Chapter 2 of this thesis reviews and classifies selected static reactive power compensators presented in the literature.

A hybrid approach that combines the above two approaches to achieve each of their best features (high power level and an interface free of harmonic interaction) simultaneously is investigated in this thesis. This hybrid approach brings together the high power capability of a thyristor controlled reactance network (Static VAr Compensator -

SVC) and the harmonic free interface of a forced commutated converter (Reactive Current Injector - RCI). The evolution and the operation of the hybrid reactive power compensator is presented in Chapter 3 of this thesis.

Chapter 4 deals with the stability issues of a current fed SVC. The analysis predicts the probable loss of a periodic steady state operating point when the hybrid reactive compensator system is delivering full capacity leading compensation.

The hybrid reactive power compensator is modelled in MATLAB-Simulink software. The modelling details are discussed in Chapter 5. The feasibility of this synergistic approach is confirmed by simulations and the experimental results in Chapter 6. It is illustrated in the simulation results that the system can be operated in both, lagging and leading compensation zones. The transient and steady state performance of the system is investigated in these zones. A special transient case of the system passing through the resonance zone is also included in these results.

The experimental results verifying the expression for the effective reactance of a current fed SVC are also presented in this chapter. The firing angle generator incorporated in the hybrid compensator system is based on the values of this effective reactance. An expression to derive the static transfer characteristics between the firing angle and the effective reactance is presented in the appendix. The experimental results have confirmed these theoretical results.

The hybrid compensator as studied in this thesis, focuses primarily on the RCI which injects the reactive current in the utility system. The SVC is used as a variable

reactance to give a voltage bias so as to decrease the voltage stress on the forced commutated devices used in the RCI. So the firing angle control for the SVC is enslaved to the reactive current command for the RCI in this approach. However, in order to isolate the harmonics generated by the switching of the thyristors from entering in the utility system, one may use the series connected controlled current regulator as an active filter. Thus the reactive compensation is provided by the SVC while the current regulator rejects all the harmonic content and passes only the fundamental component of the reactive current to the utility system. In this approach, the current regulation is enslaved to the operation of the SVC.

As mentioned earlier, the system as presented in this thesis suffers from the probability of losing the periodic steady state operating point at full capacity leading compensation. It may be interesting to analyze the stability issues of this other approach and compare the relative performance of the two approaches.

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APPENDIX

Derivation of the Relation between the Firing Angle and
the Total Reactance of a Current Fed Static VAR Compensator

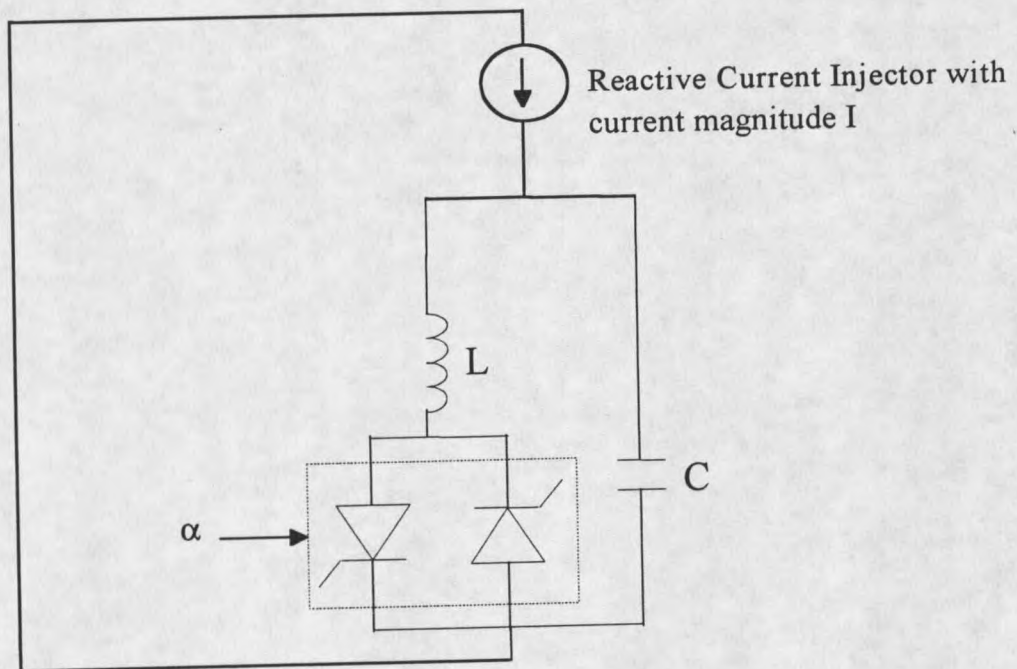


Figure 82. Simplified schematic of a current fed SVC.

The above Figure 82 shows a simplified schematic of the current fed Static VAR Compensator (SVC). The SVC is a parallel network of a variable inductance and a fixed capacitance and is used as a variable reactance network in the hybrid reactive power compensator.

The effective inductance is varied by changing the firing angle (α) and consequently varying the conduction angle (σ) of the thyristors. The typical voltage and current waveforms for this current sourced system are illustrated in Figure 83.

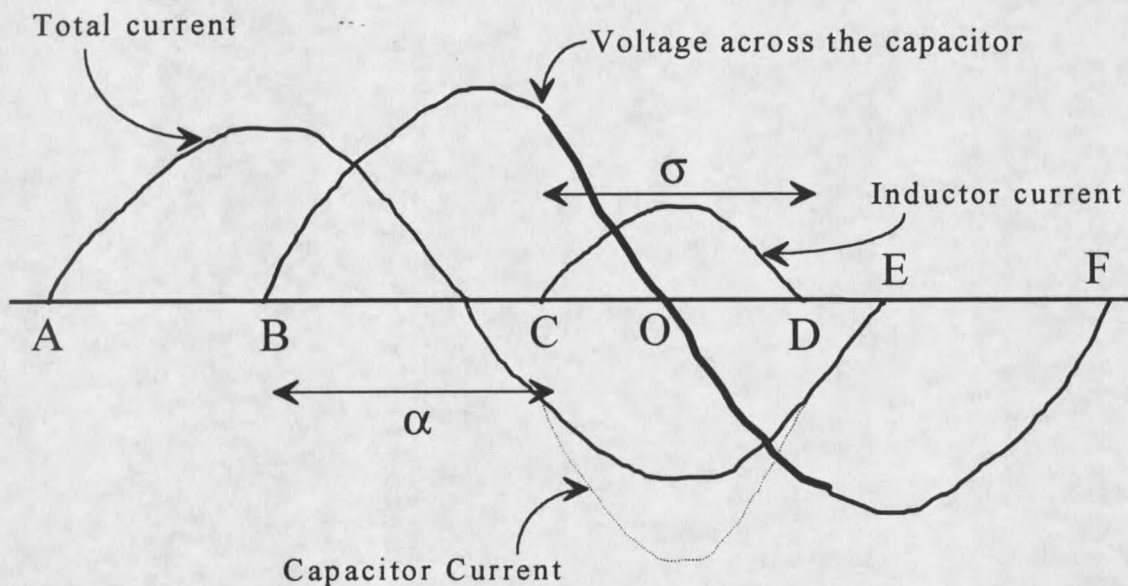


Figure 83. Typical voltage and current waveforms for the current fed SVC for one current cycle.

The above Figure 83 shows the typical waveforms for the current fed SVC for one current cycle extending from instant A to instant E. A sinusoidal current is injected into the SVC as illustrated in this figure. As the thyristors are not turned on initially, the inductor is as good as it is disconnected, and hence the capacitor current is equal to the total current. The thyristors are fired at instant C and they conduct till the current through

them reaches zero (instant D). Since it is a current controlled system, the total current is still sinusoidal, but the capacitor current exhibits the nonlinearity when the inductor is drawing the current for a fraction of the cycle (it is shown by dotted line from instant C to D). This affects the voltage across the capacitor, which is also the voltage across the L-C network. Before the thyristors are fired, the voltage is sinusoidal and lagging with respect to the capacitor current by 90° . But during the conduction period (σ) of the thyristors, the capacitor current is nonlinear and hence the voltage is also nonlinear which is illustrated by the thick line (from instant C to D). Now the inductor current in turn depends on this total voltage, and hence it is not a simple fractional sinusoidal waveform as it would be for a voltage sourced system or for a conventional SVC. On account of this non-linearity in the voltage, the inductor current also exhibits some non-linearity.

Assuming the instant O to be the origin, this current can be expressed as,

$$\begin{array}{ll} I_{inductor} = 0 & -\frac{\pi}{2} \leq \theta \leq -\frac{\sigma}{2} \\ I_L & -\frac{\sigma}{2} \leq \theta \leq \frac{\sigma}{2} \\ 0 & \frac{\sigma}{2} \leq \theta \leq \frac{\pi}{2} \end{array} \quad (A.1)$$

where I_L is quantity of interest which needs to be determined.

The injected and the capacitor current waveforms can also be expressed in terms of trigonometric quantities as follows;

$$I_{injected} = -I \cos \theta \quad (A.2)$$

where I is the magnitude of the source current (which is also equal to the compensation current).

$$\begin{array}{ll}
 I_{\text{capacitor}} = -I \cos \theta & -\frac{\pi}{2} \leq \theta \leq -\frac{\sigma}{2} \\
 -I \cos \theta - I_L & -\frac{\sigma}{2} \leq \theta \leq \frac{\sigma}{2} \\
 -I \cos \theta & \frac{\sigma}{2} \leq \theta \leq \frac{\pi}{2}
 \end{array} \quad (\text{A.3})$$

It may be noticed that capacitor current is only the difference between the injected current and the inductor current:

For the region of interest, that is for θ varying from $-\sigma/2$ to $\sigma/2$, capacitor current and voltage are given by

$$I_C = -I \cos \theta - I_L \quad (\text{A.4})$$

$$V_C = \frac{1}{\omega C} \int (-I \cos \theta - I_L) d\theta \quad (\text{A.5})$$

where ω is the supply frequency.

But the inductor current I_L is

$$I_L = \frac{1}{\omega L} \int V_C d\theta \quad (\text{A.6})$$

Hence, expression (A.5) becomes

$$V_C = \frac{1}{\omega C} \int \{-I \cos \theta - [\frac{1}{\omega L} \int V_C d\theta]\} d\theta \quad (\text{A.7})$$

Differentiating expression (A.7) twice with respect to θ , we get

$$\frac{d^2 V_C}{d\theta^2} = \frac{1}{\omega C} I \sin \theta - \frac{1}{\omega^2 LC} V_C \quad (\text{A.8})$$

This is a non-homogenous second order differential equation.

The solution of this differential equation is composed of a Complementary Function (CF) which is given by

$$CF = P \sin \frac{\theta}{\omega \sqrt{LC}} + Q \cos \frac{\theta}{\omega \sqrt{LC}} \quad (A.9)$$

and a Particular Integral (PI) which is

$$PI = R \sin \theta \quad (A.10)$$

where P , Q and R are constants.

Thus, the complete solution for the capacitor voltage is

$$V_C = P \sin \frac{\theta}{\omega \sqrt{LC}} + Q \cos \frac{\theta}{\omega \sqrt{LC}} + R \sin \theta \quad (A.11)$$

It may be noticed that the capacitor voltage has three components, one is $R \sin \theta$ which is on account of the forced current, and the other two are the functions of the resonance frequency (ω_o) of the L-C network, where $\omega_o = \frac{1}{\sqrt{LC}}$.

To evaluate the constants P , Q and R , differentiating expression (A.11) twice with respect to θ we get,

$$\frac{d^2 V_C}{d\theta^2} = -\frac{P}{\omega^2 LC} \sin \frac{\theta}{\omega \sqrt{LC}} - \frac{Q}{\omega^2 LC} \cos \frac{\theta}{\omega \sqrt{LC}} - R \sin \theta \quad (A.12)$$

Substituting expression (A.12) in differential equation (A.8),

$$-\frac{P}{\omega^2 LC} \sin \frac{\theta}{\omega \sqrt{LC}} - \frac{Q}{\omega^2 LC} \cos \frac{\theta}{\omega \sqrt{LC}} - R \sin \theta = \frac{1}{\omega C} I \sin \theta - \frac{1}{\omega^2 LC} \left\{ P \sin \frac{\theta}{\omega \sqrt{LC}} + Q \cos \frac{\theta}{\omega \sqrt{LC}} + R \sin \theta \right\} \quad (\text{A.13})$$

From expression (A.13), we get the value of R as

$$R = \frac{\omega L}{1 - \omega^2 LC} I \quad (\text{A.14})$$

So, the capacitor voltage becomes

$$V_C = P \sin \frac{\theta}{\omega \sqrt{LC}} + Q \cos \frac{\theta}{\omega \sqrt{LC}} + \frac{\omega L}{1 - \omega^2 LC} I \sin \theta \quad (\text{A.15})$$

Differentiating this with respect to θ we get the capacitor current as

$$I_C = \omega C \frac{dV_C}{d\theta} = P \sqrt{\frac{C}{L}} \cos \frac{\theta}{\omega \sqrt{LC}} - Q \sqrt{\frac{C}{L}} \sin \frac{\theta}{\omega \sqrt{LC}} + \frac{\omega^2 LC}{1 - \omega^2 LC} I \cos \theta \quad (\text{A.16})$$

Substituting this value of I_C in expression (A.3)

$$-I \cos \theta - I_L = P \sqrt{\frac{C}{L}} \cos \frac{\theta}{\omega \sqrt{LC}} - Q \sqrt{\frac{C}{L}} \sin \frac{\theta}{\omega \sqrt{LC}} + \frac{\omega^2 LC}{1 - \omega^2 LC} I \cos \theta \quad (\text{A.17})$$

Hence, we get the inductor current I_L to be

$$I_L = -I \cos \theta - P \sqrt{\frac{C}{L}} \cos \frac{\theta}{\omega \sqrt{LC}} + Q \sqrt{\frac{C}{L}} \sin \frac{\theta}{\omega \sqrt{LC}} - \frac{\omega^2 LC}{1 - \omega^2 LC} I \cos \theta \quad (\text{A.18})$$

As inductor current is 0 at $\theta = \sigma/2$ and at $\theta = -\sigma/2$, we get the two simultaneous equations in P and Q as follows

$$-\frac{1}{1 - \omega^2 LC} I \cos \frac{\sigma}{2} - P \sqrt{\frac{C}{L}} \cos \frac{\sigma/2}{\omega \sqrt{LC}} + Q \sqrt{\frac{C}{L}} \sin \frac{\sigma/2}{\omega \sqrt{LC}} = 0 \quad (\text{A.19})$$

$$-\frac{1}{1 - \omega^2 LC} I \cos \frac{\sigma}{2} - P \sqrt{\frac{C}{L}} \cos \frac{\sigma/2}{\omega \sqrt{LC}} - Q \sqrt{\frac{C}{L}} \sin \frac{\sigma/2}{\omega \sqrt{LC}} = 0 \quad (\text{A.20})$$

Solving these equations (A.19) and (A.20), the value of Q can be found to be 0

and value of P is

$$P = -I\sqrt{\frac{L}{C}} \frac{1}{1-\omega^2 LC} \frac{\cos \frac{\sigma}{2}}{\cos \frac{\sigma/2}{\omega\sqrt{LC}}} \quad (\text{A.21})$$

So the capacitor voltage becomes

$$V_C = -I\sqrt{\frac{L}{C}} \frac{1}{1-\omega^2 LC} \frac{\cos \frac{\sigma}{2}}{\cos \frac{\sigma/2}{\omega\sqrt{LC}}} \sin \frac{\theta}{\omega\sqrt{LC}} + \frac{\omega L}{1-\omega^2 LC} I \sin \theta \quad (\text{A.22})$$

Also, the inductor current can be found from expression (A.18) as

$$I_L = -\frac{1}{1-\omega^2 LC} I \cos \theta + I \frac{1}{1-\omega^2 LC} \frac{\cos \frac{\sigma}{2}}{\cos \frac{\sigma/2}{\omega\sqrt{LC}}} \cos \frac{\theta}{\omega\sqrt{LC}} \quad (\text{A.23})$$

To find the fundamental component of this inductor current, it can be expressed in Fourier series as follows

$$I_L = a_0 + \sum a_n \cos(n\theta) \quad (\text{A.24})$$

$$\text{where } a_n = \frac{2}{\pi} \int I_L \cos(n\theta) d\theta \quad n = 0, 1, \dots$$

and limits of integration are $0, \pi$

So, the fundamental component of the inductor current is $a_1 \cos \theta$ which can be found as

$$I_{L_{funda}} = -I \frac{1}{1-\omega^2 LC} \frac{1}{\pi} \left\{ \sigma + \sin \frac{\sigma}{2} - \frac{4 \cos^2 \sigma/2}{1 - \frac{1}{\omega^2 LC}} \left[\tan \frac{\sigma}{2} - \frac{1}{\omega\sqrt{LC}} \tan \frac{\sigma/2}{\omega\sqrt{LC}} \right] \right\} \cos \theta \quad (\text{A.25})$$

From expression (A.3), the fundamental component of capacitor current can be found to be

$$I_{C_{funda}} = I \frac{1}{1-\omega^2 LC} \frac{1}{\pi} \left\{ \sigma + \sin \frac{\sigma}{2} - \frac{4 \cos^2 \sigma/2}{1 - \frac{1}{\omega^2 LC}} \left[\tan \frac{\sigma}{2} - \frac{1}{\omega\sqrt{LC}} \tan \frac{\sigma/2}{\omega\sqrt{LC}} \right] \right\} \cos \theta - I \cos \theta \quad (\text{A.26})$$

Hence, the fundamental voltage across the capacitor, and thus across the total L-C network is

$$V_{C_{funda}} = I_{C_{funda}} X_C \quad (A.27)$$

where, X_C is the reactance of the capacitor.

So the equivalent reactance of this network is given as

$$X_{eq} = \frac{V_{C_{funda}}}{I_{injected}} \quad (A.28)$$

$$\text{where} \quad I_{injected} = -I \cos \theta \quad (A.2)$$

Thus, the relation between the equivalent reactance of the current fed SVC (X_{eq}) and the firing angle (α) can be found to be as

$$X_{eq} = X_C \left\{ 1 - \frac{A(\sigma + \sin \sigma)}{\pi} + \frac{4A \cos^2 \frac{\sigma}{2} [K \tan(K \frac{\sigma}{2}) - \tan \frac{\sigma}{2}]}{\pi(K^2 - 1)} \right\} \quad (A.29)$$

$$\text{where} \quad K = \frac{\omega_o}{\omega} \quad (A.30)$$

$$\omega_o^2 = \frac{1}{LC} \quad (A.31)$$

$$A = \frac{\omega_o^2}{\omega_o^2 - \omega^2} \quad (A.32)$$

$$X_C = \frac{1}{\omega C} \quad (A.33)$$

$$\frac{\sigma}{2} = \pi - \alpha \quad (A.34)$$

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