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,
Montana State University

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.

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

MONTANA STATE UNIVERSITY-BOZEMAN

Bozeman, Montana

August 1997

APPROVAL

of a thesis submitted by

Madhav D. Manjrekar

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.

Giri Venkataramanan — V. Venkataramanan (Signature) — 25 Aug 1997 Date

Approved for the Department of Electrical Engineering

Bruce McLeod — Bruce R. McLeod (Signature) — 8-25-97 Date

Approved for the College of Graduate Studies

Joseph J. Fedock (Signature) — 8/26/97 Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature [signature]

Date August 25th, 1997

ACKNOWLEDGEMENTS

The author would like to acknowledge the support of the National Science Foundation (Grant Number ECS-9308598) and Montana Electric Power Research Association in funding the research documented in this thesis.

I wish to take this opportunity to express my gratitude to Dr. Giri Venkataramanan for his support and encouragement. It has indeed been a great pleasure to work with him. He has always made himself available assuming various forms; as a respected teacher, a caring guardian, a helpful friend and an affectionate brother in my hour of need.

I would also like to thank the faculty, staff and my colleagues in the Department of Electrical Engineering, Montana State University who made my stay in Bozeman a rich and rewarding experience.

Madhav D. Manjrekar

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

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 condensor 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 condensors, 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.

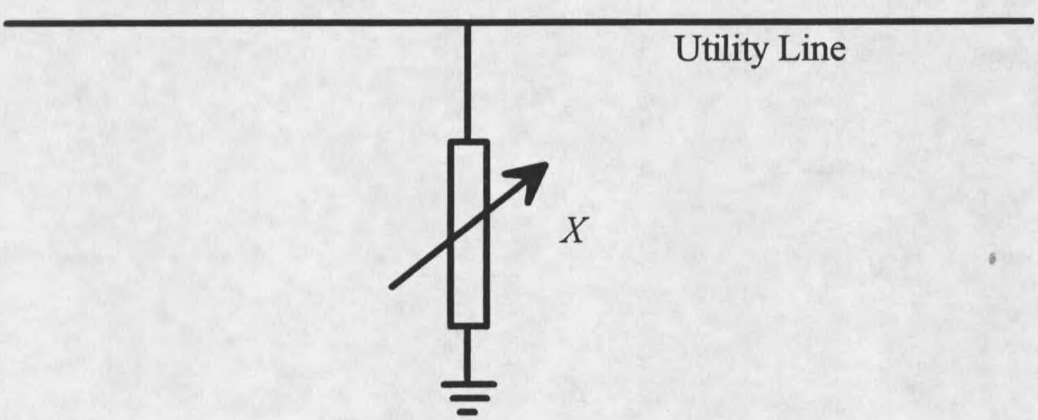

Figure 1. Variable reactance type compensator.

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].

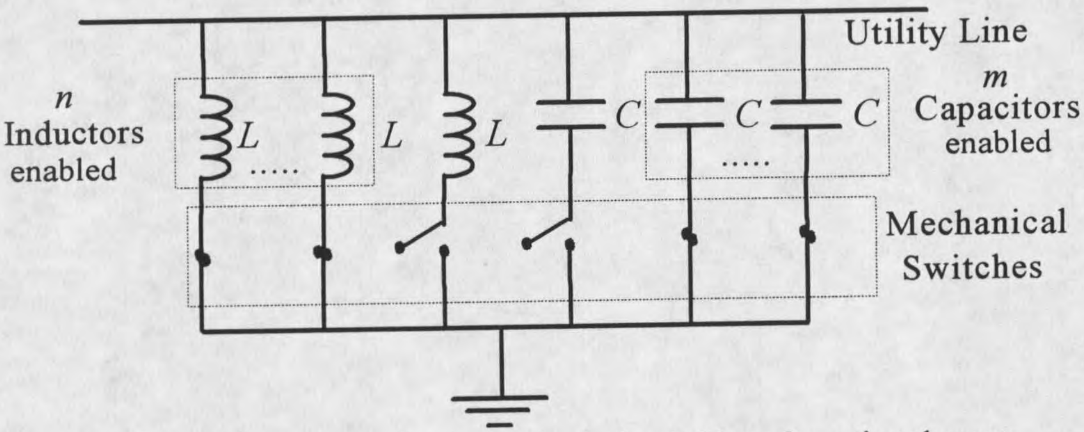

Figure 2. Variable compensation by mechanical switching of reactive elements.

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

$$X = \frac{j\omega L}{n} \,||\, \frac{1}{jm\omega C} \tag{2.1}$$

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.

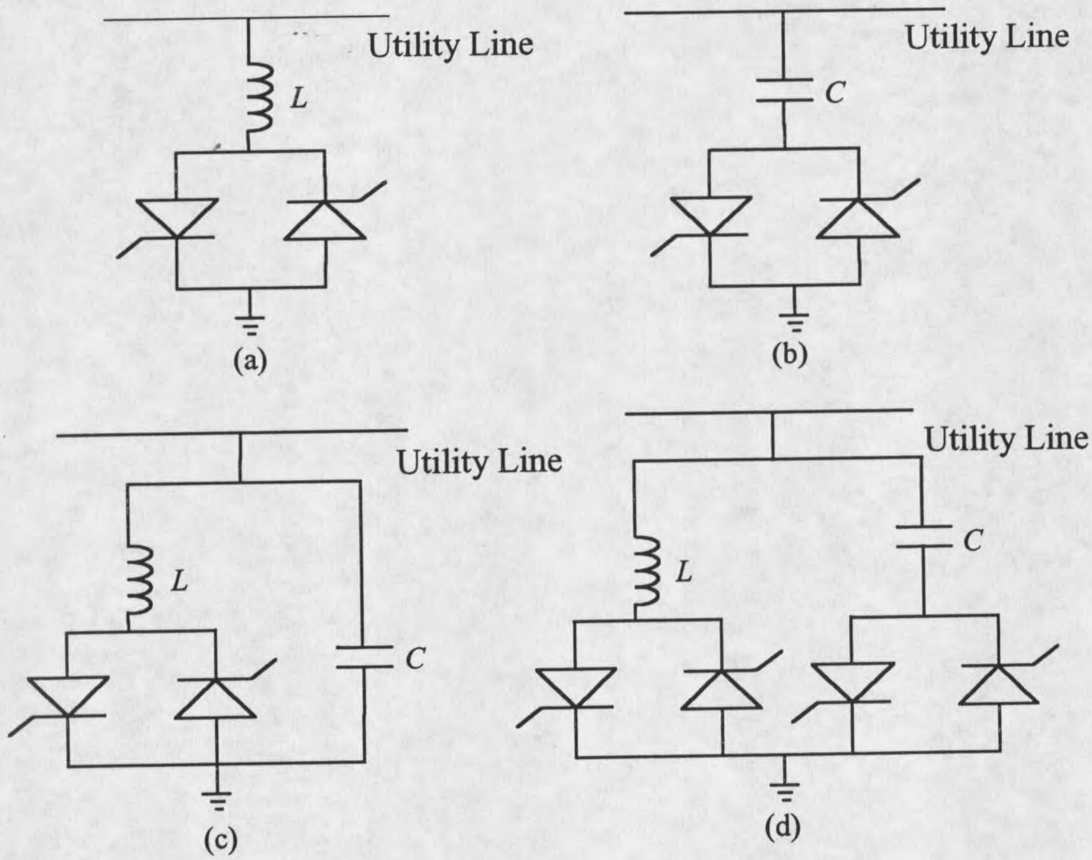

Figure 3. Various configurations of variable reactance type compensators :
(a) Thyristor Controlled Reactor (TCR)
(b) Thyristor Switched Capacitor (TSC)
(c) Static VAr Compensator (SVC)
(d) TCR parallel with TSC