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HARMONICS AND INSTABILITIES IN THYRISTOR BASED SWITCHING CIRCUITS

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This thesis investigates nonlinear dynamics, harmonic distortions and bifurcation instabilities in thyristor switching circuits. The analysis is directed towards the study of a Thyristor Controlled Reactor (TCR) which consists of a fixed reactor and two oppositely poled thyristors. The dependence of the thyristor switching times on the system states causes the circuit nonlinearities and is the focus of much of the thesis. New concepts for instability, dynamic response and damping for TCR circuits are introduced. These concepts are general and can be extended to other switching circuits. Useful TCR circuit examples such as the 230 kV Kayenta advanced series compensator and the 230 kV Rimouski static Var system are used to numerically verify these concepts. We have found new instabilities in both the Kayenta and the Rimouski systems in which switching times change suddenly, or bifurcate as a system parameter varies slowly. Switching time bifurcations are associated with large distortions of the TCR current or voltage waveforms leading to a new earlier TCR current zero, the disappearance of a current zero, or a

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My numerous meetings with Professor Lasseter helped me to define the problem and to keep in touch with the practical issues regarding it. Similarly, my numerous discussions with Professor Dobson provided me with the theoretical framework required in solving this problem.

The past three years of working together has given me the confidence to become an independent researcher, for which I am thankful.

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Chapter 1

Introduction

Over the last couple of years there has been significant activity in the development of Flexible AC Transmission Systems (FACTS). Much of this work has been directed towards advanced series compensation (ASC) systems based on a thyristor controlled reactor connected in parallel with a fixed capacitor [8,9,17,18,28]. This results in a controllable series impedance element for use in transmission systems. As static switching circuits such as FACTS proliferate, there is an increasing need to analyze and understand these circuits and their interactions with power systems. However, because of the dependence of the thyristor turn on and off times on the system states, thyristor switching circuits are nonlinear and very awkward to analyze using standard mathematical techniques [17,25].

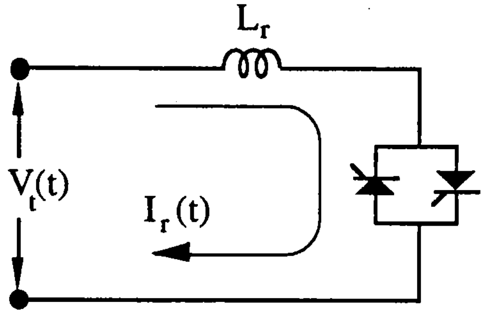

Figure 1.1. Basic single phase TCR

This thesis will use the Thyristor Controlled Reactor (TCR) circuit shown in the Figure 1.1 as an illustrative example for study. This circuit is a good choice for developing new techniques of analysis since the number of switching elements is small. Two useful TCR circuits are the associated with the thyristor switching times, it is still one of the most common methods of computing eigenvalues [11,16,23,33]. We have found the average inductor model very useful in approximately predicting potential resonance points.

4) The dynamics of a switching circuits may be studied using state space averaging. It can be shown that averaging the state space equations is a good approximation for the pulse-width modulated convertors [34]. On the other hand, it can give incorrect results for the naturally commutated circuits such as the resonant link converters or the TCR circuits. Sanders in [39] extends this method to study the convertors which switch at lower frequencies by adding higher order correction terms to the classical formulation. However, it is not clear how this method can be used to study circuits with discontinuous modes of operation such as the thyristor controlled reactor.

5) The nonlinear dynamics of a TCR circuit were studied using the Poincare mapping from the dynamical systems theory [20,46]. In this approach, the system state is strobed at discrete times which are spaced by one period of the fundamental frequency, T and the system is studied by means of the Poincare map. The Poincare map advances the system state from one discrete time to the system state at the next discrete time. If the circuit has a steady state solution of period T, then the Poincare map has a fixed point. Except for marginal cases, the Poincare map can be differentiated and a formula for its Jacobian can be obtained. The Jacobian of the Poincare map evaluated at the fixed point can be used to

6) The harmonics of a power system which include a three phase thyristor bridge may be computed using the harmonic power flow method [51,52]. In this method, the AC current flowing into the converter terminal is solved in terms of the convertor AC voltage. One of the drawbacks is that the DC load is assumed to be a series combination of a resistor, inductor and a DC source. Another drawback is that the harmonic interactions of the converter and power system can not be studied when ambient even harmonics are present.

7) Peter Wood in [50] introduced the switching function method to compute the harmonics generated by converters which have fixed switching times. Bohmann and Lasseter extended this method to TCR circuits [7]. By expressing the TCR voltage and current as a Fourier series, a TCR harmonic admittance matrix is constructed. The admittance matrix is then incorporated into a power system providing a quick and general method to compute the power system harmonics. This method is explained in detail in chapter 3 and is used in chapter 5 to compute the harmonics of TCR circuits.

Classical analysis is often applicable, but can as demonstrated in this thesis and in [7,9] fail for certain circuit parameters and operating conditions. Under these conditions, both the voltage and the current waveforms become greatly distorted with large harmonic components. This phenomena is due to the circuit operating close to its resonance point and can be detected by the eigenvalues of the half wave Poincare map being -1.

coupling matrix which illustrates the coupling between the convertor voltage and current harmonics is developed. It is shown how this matrix can be incorporated into a power system and how the power system harmonics can be accurately calculated. In addition, an example system which exhibits large harmonic distortions and switching time bifurcation is also presented. In particular, it is shows that there may be two steady state solutions and/or no solutions over the regions for which the classical method predicts both the existence and the uniqueness of the solution.

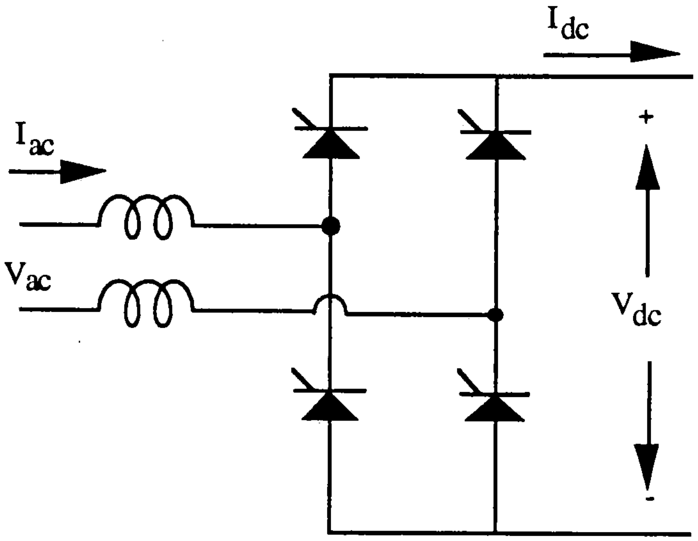

Figure 1.2 Single phase line commutated converter

Chapter 2

Thyristor Controlled Reactor (TCR)

Thyristor controlled reactors are typically composed of back to back thyristors used to vary the duty cycle of an inductor. In periodic steady state, the effect of the 60 Hz fundamental is to absorb varying amounts of reactive power from a power system network. Figure 2.1 shows a basic single phase Thyristor Controlled Reactor (TCR). It consists of a fixed reactor of inductance L (usually air core) and two oppositely poled thyristors which conduct on alternate half cycles of the supply frequency.

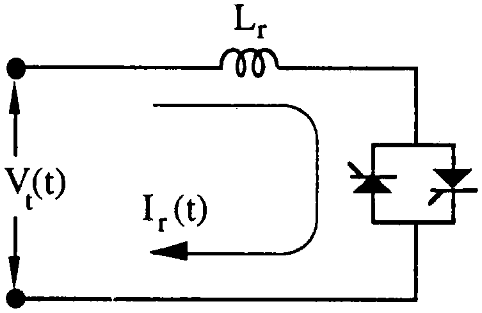

Figure 2.1. Basic single phase TCR

A thyristor conducts current only in the forward direction, can block voltage in both directions, turns on when a firing signal is provided and turns off after a current zero. The currently available thyristors can block a voltage range between 4000 to 6000 volts and can carry a current ranging from 2000 to 4000 amperes. In general, between 10 to 40 thyristor valves are connected in series to meet the required blocking voltage levels [21].

2.1 Two circuit examples using TCR

To illustrate some of the potential problems associated with the operation of TCR switching circuits and methods developed in this report, this section introduces two commonly used TCR circuits. These circuits are a single phase static VAR compensator and a single phase advanced series compensator.

The Static Var Compensator (SVC)

Figure 2.3 shows a SVC consisting of a thyristor controlled reactor (TCR) and a parallel capacitor. This system is connected to an infinite bus behind a power system impedance of an inductance L_s and a resistance R_s in series. The controlled reactor is modelled as a series combination of an inductor L_r and R_r.

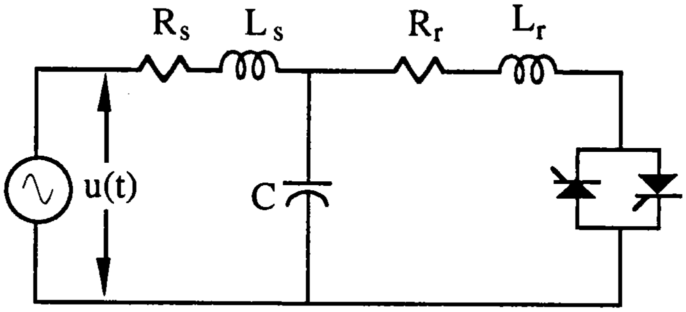

Figure 2.3. Single phase static VAR system

The above circuit can provide leading to lagging reactive power to the AC system. This characteristic behavior of the 60 Hz fundamental is approximately equivalent to an ideal system voltage source at the point of connection except that it has a limited range in which the voltage can be controlled.

been directed towards advanced series compensation (ASC) systems based on a thyristor controlled reactor connected in parallel with a fixed capacitor. This results in a controllable series impedance element for use in transmission systems.

Currently there are three such systems in various stages of commercialization. The Kanayna River system, West Virginia, is a joint R&D effort by American Electric Power Service Corporation and Asea Brown Boveri. This FACTS controller has been recently commissioned [32]. The system was planned to have 788 Mvar of series capacitance or 60% compensation. In the first phase of the project a prototype thyristor control module has been installed across one phase of 131 Mvar of compensation to create an ASC system. The remaining two phases will be installed following successful testing of this unit.

Western Area Power Administration is installing a 230 kV, 330 Mvar ASC system in northeastern Arizona at Kayenta Substation [8]. This system is supplied by Siemens AG. This scheme is comprised of 285 Mvar of conventional series capacitor banks with the remaining 45 Mvar of capacitance controlled by a parallel thyristor controlled reactor. Implementation of this FACTS scheme has progressed through the equipment development phases and currently is been installed at the site.

A third scheme is a major Electric Power Research Institute project with General Electric to develop a thyristor controlled series capacitor. A second phase of this project is to install such a system on a 500 kV transmission line in the Bonneville Power Administration region. This

2.2 Control methods and firing strategies

This section discusses the basic control issues and various firing schemes which are used to operate the TCR circuits.

Basic control scheme

Figure 2.5 shows a basic TCR control scheme with three function blocks. The first is the interface block which computes the root mean square of the TCR voltage. The second block is the regulator block. The input to this block is the difference between the reference quantities V_{ref} and the measured quantities V_{rms} and the output is a request value for either the thyristor conduction time σ or the firing delay α. The third block, the gate pulse generator, generates the firing pulses for the thyristors. The gate pulse generator usually uses one of the synchronization schemes described below so as to achieve the requested σ or α.

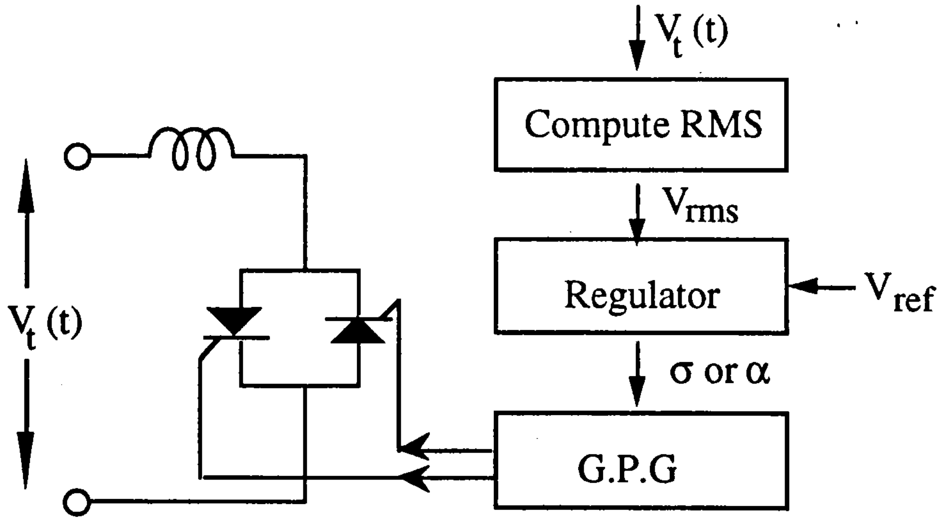

Figure 2.5. Control scheme for the TCR

parameter V_c. The phase of the equally spaced firing pulses has some arbitrary value with respect to the voltage across the TCR. In practice, this phase would drift relative to the TCR voltage. This is usually corrected by an external negative feedback loop.

An alternative to the phase locked loop scheme is shown in Figure 2.6 [4]. In this method, the firing pulses are sent whenever the integrator function V_{cf} intersects the controller output voltage V_c. At this point, the integrator V_{cf} is reset and the integration process starts again. The integrator function and the controller output voltage are chosen such that the firing pulses are spaced by 180 electrical degrees so that there are two firing pulses per cycle.

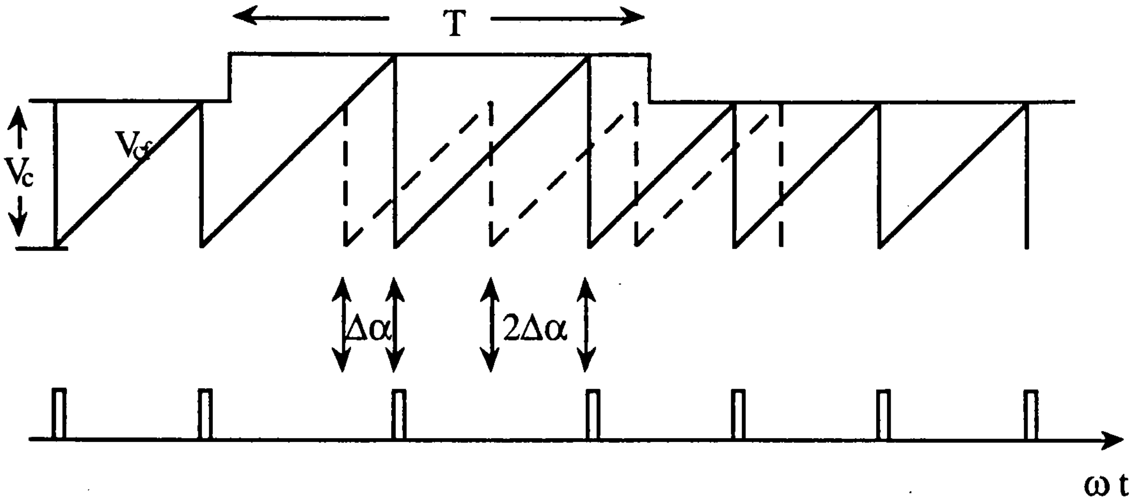

Figure 2.6. Firing pulses using the equidistant firing scheme

Figure 2.6 illustrates how the relative phase of the firing pulses can be changed by temporarily varying the control signal V_c. Let us assume that the firing pulses have initially a delay angle α with respect to the actual system. As long as the controller output voltage is fixed, α is also fixed conduction and 1.0 when conduction. Integrating this signal results in an output which exhibits a slope change at the point where conduction stops. The output of the integrator is negatively biased by a constant value of 2π as shown in the Figure 2.7c. This signal is input to a zero plus detector which issues the firing pulses whenever the signal becomes positive. The resulting firing pulses are shown in the Figure 2.7d.

The main advantage of this scheme is that there is no need for accurate measurement of either voltage or current.

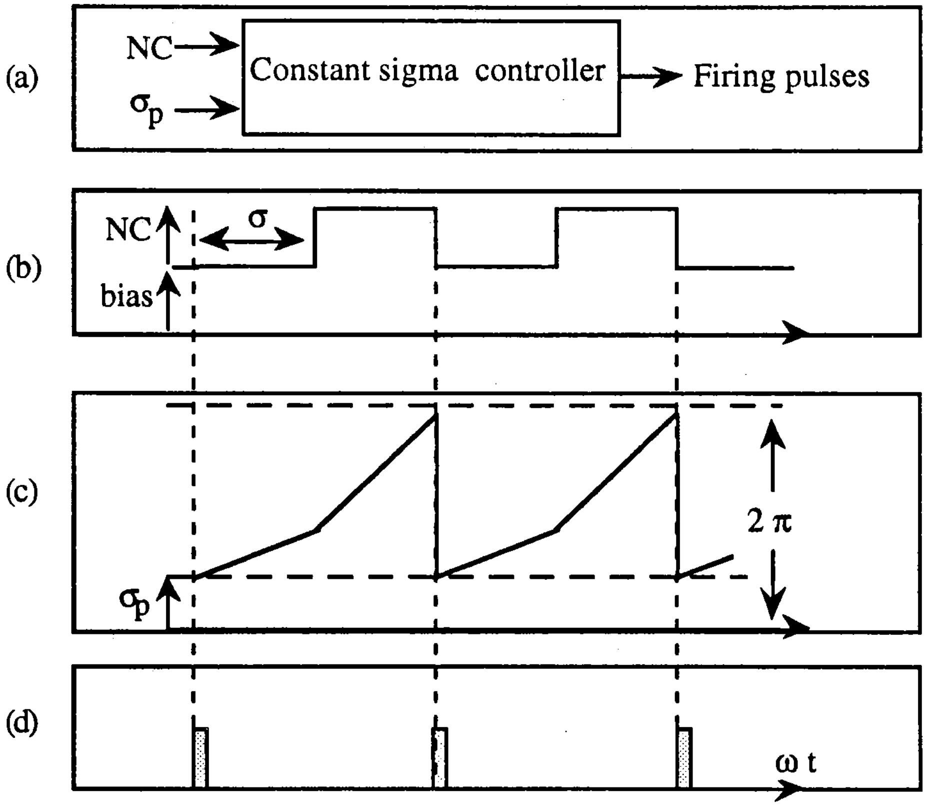

Figure 2.7. The constant sigma controller

Chapter 3

Tools to Study the Thyristor Controlled Reactor

A thyristor controlled reactor (TCR) is a thyristor based compensator which is capable of absorbing reactive power from a power system network. In chapter 2, issues associated with the control and operation and firing strategies for two useful TCR circuits were studied. These two TCR circuits are, the Static Var Compensator (SVC) and the Advanced Series Compensator (ASC) shown in Figures 1 and 2.

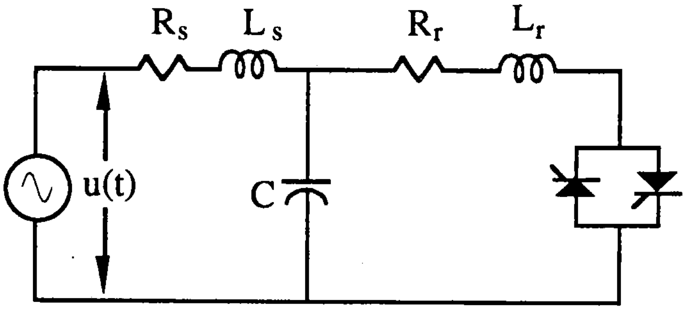

Figure 3.1. Single phase static VAR compensator

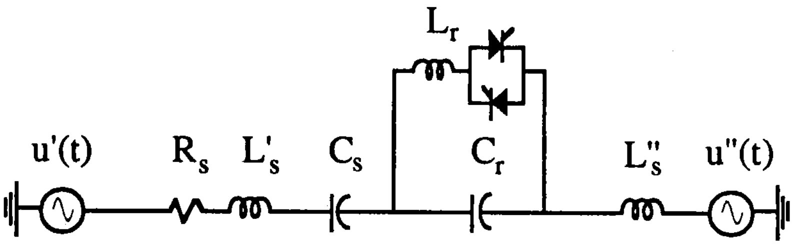

Figure 3.2. Advanced series compensator

In section 3.1, the classical method of computing the system harmonics is explained. Section 3.2 introduces a simple average inductor model useful in approximately predicting potential problems with the operation