FACTS

Modelling and Simulation in Power Networks

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To Our Beloved Families

Contents

Preface

Flexible alternating-current transmission systems (FACTS) is a recent technological development in electrical power systems. It builds on the great many advances achieved in high-current, high-power semiconductor device technology, digital control and signals conditioning. From the power systems engineering perspective, the wealth of experience gained with the commissioning and operation of high-voltage direct-current (HVDC) links and static VAR compensator (SVC) systems, over many decades, in many parts of the globe, may have provided the driving force for searching deeper into the use of emerging power electronic equipment and techniques, as a means of alleviating long-standing operational problems in both high-voltage transmission and low-voltage distribution systems. A large number of researchers have contributed to the rapid advancement of the FACTS technology, but the names N.G. Hingorani and L. Gyugyi stand out prominently. Their work on FACTS, synthesised in their book, *Understanding FACT – Concepts and Technology of Flexible AC Transmission Systems* (Institute of Electronic and Electrical Engineers, New York, 2000), is a source of learning and inspiration.

Following universal acceptance of the FACTS technology and the commissioning of a vast array of controllers in both high-voltage transmission and low voltage distribution systems, research attention turned to the steady-state and dynamic interaction of FACTS controllers with the power network. The research community responded vigorously, lured by the novelty of the technology, turning out a very healthy volume of advanced models and high-quality simulations and case studies. Most matters concerning steady-state modelling and simulations of FACTS controllers are well agreed on, and the goal of our current book: *FACTS: Modelling and Simulation in Power Networks*, is to provide a coherent and systematic treatise of the most popular FACTS models, their interaction with the power network, and the main steady-state operational characteristics.

The overall aims and objectives of the FACTS philosophy are outlined in Chapter 1. The inherent limitations exhibited by high-voltage transmission systems, which are inflexible and overdesigned, are brought to attention as a means of explaining the background against which the FACTS technology developed and took hold. The most promising FACTS controllers and their range of steady-state applicability are described in this chapter.

Chapters 2 and 3 provide a thorough grounding on the mathematical representation of the most popular FACTS controllers and power plant components. The models are derived from first principles: by encapsulating the main steady-state operational characteristics and physical structure of the actual equipment, advanced power system models are developed in phase coordinates. As a by-product, more restrictive models are then derived, which are suitable for positive sequence power system analysis. Software written in Matlab® code is given for the most involved aspects of power plant modelling, such as transmission Line parameter calculation.

The power flow method is the most basic system analysis tool with which to assess the steady-state operation of a power system. It has been in existence for almost half a century, having reached quite a sophisticated level of development, in terms of both computational efficiency and modelling flexibility. The Newton–Raphson method is the *de facto* standard for solving the nonlinear power equations, which describe the power systems, owing to its reliability towards convergence. Chapter 4 covers the theory of positive sequence power flow in depth, and makes extensions to incorporate cases of adjusted solutions using two conventional power system controllers. This serves as a preamble to the material presented in Chapter 5, where a wide range of positive sequence power flow models of FACTS controllers are developed. Test cases and software written in Matlab® code is provided for each controller to enable the reader to gain ample experience with the various models provided. Furthermore, suitable coding of the Jacobian elements given in Appendix A enables more general FACTS power flow computer programs than those given in Chapter 5.

The concepts used in the study of positive sequence power flow in Chapters 4 and 5 are extended in Chapter 6 to address the more involved topic of three-phase power flow. The first part deals with the Newton–Raphson in-phase coordinates using simplified representations of conventional power plant components. Software written in Matlab® code is provided to enable the solution of small and medium-size three-phase power systems. Advanced models of conventional power plants are not included in the Matlab® function given in this chapter but their incorporation is a straightforward programming exercise. The second half of Chapter 6 addresses the modelling of three-phase controllers within the context of the power flow Newton–Raphson method, where the voltage and power flow balancing capabilities of shunt and series FACTS controllers, respectively, are discussed.

The topic of optimal power flow is covered in depth in Chapter 7. Building on the ground covered in Chapters 4 and 5, the theory of positive sequence power flow is blended with advanced optimisation techniques to incorporate economic and security aspects of power system operation. The optimisation method studied in this chapter is Newton's method, which exhibits strong convergence and fits in well with the modelling philosophy developed throughout the book. Both conventional plant equipment and FACTS controller representations are accommodated with ease within the frame of reference provided by Newton's method. To facilitate the extension of a conventional optimal power flow computer program to include FACTS representation, Appendix B gives the Hessian and gradient elements for all the FACTS controllers presented in Chapter 7. Software written in Matlab® code is provided in Appendix C to carry out non-FACTS optimal power flow solutions of small and medium-size power systems. The timely issue of power flow tracing is presented in Chapter 8. The method is based on the principle of proportional sharing and yields unambiguous information on the contribution of each generator to each transmission Line power flow and load in the system. Several application examples are presented in the chapter.

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The preparation of the book is a testimony to international collaboration, overcoming fixed work commitments, continental distances, and widely differing time zones to bring the project to fruition: we would like to thank our respective families for the time that we were kindly spared throughout the duration of the project. In this tenor, we would also like to acknowledge the unstinting support of our colleagues in the Power Engineering Group at the

University of Glasgow. The research work underpinning most of the new modelling concepts and methods presented in this book were carried out at the University of Glasgow by the authors over a period of more than 10 years. We would like to thank Mr Colin Tan Soon Guan and Dr Jesus Rico Melgoza for their early contribution to the research project. It is fair to say that the dream was only made possible by the generous support of the role model for all research councils in the world, the Consejo Nacional de Ciencia y Tecnología (CONACYT), México. The dream goes on . . . thanks CONACYT.

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1

Introduction

1.1 BACKGROUND

The electricity supply industry is undergoing a profound transformation worldwide. Market forces, scarcer natural resources, and an *everincreasing* demand for electricity are some of the drivers responsible for such an unprecedented change. Against this background of rapid evolution, the expansion programmes of many utilities are being thwarted by a variety of well-founded, environmental, land-use, and regulatory pressures that prevent the licensing and building of new transmission lines and electricity generating plants. An in-depth analysis of the options available for maximising existing transmission assets, with high levels of reliability and stability, has pointed in the direction of power electronics. There is general agreement that novel power electronics equipment and techniques are potential substitutes for conventional solutions, which are normally based on electromechanical technologies that have slow response times and high maintenance costs (Hingorani and Gyugyi, 2000; Song and Johns, 1999).

An electrical power system can be seen as the interconnection of generating sources and customer loads through a network of transmission lines, transformers, and ancillary equipment. Its structure has many variations that are the result of a legacy of economic, political, engineering, and environmental decisions. Based on their structure, power systems can be broadly classified into meshed and longitudinal systems. Meshed systems can be found in regions with a high population density and where it is possible to build power stations close to load demand centres. Longitudinal systems are found in regions where large amounts of power have to be transmitted over long distances from power stations to load demand centres.

Independent of the structure of a power system, the power flows throughout the network are largely distributed as a function of transmission line impedance; a transmission line with low impedance enables larger power flows through it than does a transmission line with high impedance. This is not always the most desirable outcome because quite often it gives rise to a myriad of operational problems; the job of the system operator is to intervene to try to achieve power flow redistribution, but with limited success. Examples of operating problems to which unregulated active and reactive power flows may give rise are: loss of system stability, power flow loops, high transmission losses, voltage limit violations, an inability to utilise transmission line capability up to the thermal limit, and cascade tripping.

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In the long term, such problems have traditionally been solved by building new power plants and transmission lines, a solution that is costly to implement and that involves long construction times and opposition from pressure groups. It is envisaged that a new solution to such operational problems will rely on the upgrading of existing transmission corridors by using the latest power electronic equipment and methods, a new technological thinking that comes under the generic title of FACTS – an acronym for flexible alternating current transmission systems.

1.2 FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

In its most general expression, the FACTS concept is based on the substantial incorporation of power electronic devices and methods into the high-voltage side of the network, to make it electronically controllable (IEEE/CIGRÉ, 1995).

Many of the ideas upon which the foundation of FACTS rests evolved over a period of many decades. Nevertheless, FACTS, an integrated philosophy, is a novel concept that was brought to fruition during the 1980s at the Electric Power Research Institute (EPRI), the utility arm of North American utilities (Hingorani and Gyugyi, 2000). FACTS looks at ways of capitalising on the many breakthroughs taking place in the area of high-voltage and high-current power electronics, aiming at increasing the control of power flows in the high-voltage side of the network during both steady-state and transient conditions. The new reality of making the power network electronically controllable has started to alter the way power plant equipment is designed and built as well as the thinking and procedures that go into the planning and operation of transmission and distribution networks. These developments may also affect the way energy transactions are conducted, as high-speed control of the path of the energy flow is now feasible. Owing to the many economical and technical benefits it promised, FACTS received the uninstinctive support of electrical equipment manufacturers, utilities, and research organisations around the world (Song and Johns, 1999).

Several kinds of FACTS controllers have been commissioned in various parts of the world. The most popular are: load tap changers, phase-angle regulators, static VAR compensators, thyristor-controlled series compensators, interphase power controllers, static compensators, and unified power flow controllers (IEEE/CIGRÉ, 1995).

It was recognised quite early on the development programme of the FACTS technology that, in order to determine the effectiveness of such controllers; on a networkwide basis, it would be necessary to upgrade most of the system analysis tools with which power engineers plan and operate their systems. Some of the tools that have received research attention and, to a greater or lesser extent, have reached a high degree of modelling sophistication are:

- positive sequence power flow;
- three-phase power flow;
- optimal power flow;
- state estimation;
- transient stability;
- dynamic stability;
- electromagnetic transients;
- power quality.

This book covers in breadth and depth the modelling and simulation methods required for a thorough study of the steady-state operation of electrical power systems with FACTS controllers. The first three application areas, which are clearly defined within the realm of steady-state operation, are addressed in the book. The area of FACTS state estimation is still under research and no definitive models or simulation methods have emerged, as yet. A great deal of research progress has been made on the modelling and simulation of FACTS controllers for transient and dynamic stability, electromagnetic transients, and power quality, but the simulation tools required to conduct studies in such application areas are not really suited to conduct steady-state power systems analysis, and they are not covered in this book.

1.3 INHERENT LIMITATIONS OF TRANSMISSION SYSTEMS

The characteristics of a given power system evolve with time, as load grows and generation is added. If the transmission facilities are not upgraded sufficiently the power system becomes vulnerable to steady-state and transient stability problems, as stability margins become narrower (Hingorani and Gyugyi, 2000).

The ability of the transmission system to transmit power becomes impaired by one or more of the following steady-state and dynamic limitations (Song and Johns, 1999):

- angular stability;
- voltage magnitude;
- thermal limits;
- transient stability;
- dynamic stability.

These limits define the maximum electrical power to be transmitted without causing damage to transmission lines and electric equipment. In principle, limitations on power transfer can always be relieved by the addition of new transmission and generation facilities. Alternatively, FACTS controllers can enable the same objectives to be met with no major alterations to system layout. The potential benefits brought about by FACTS controllers include reduction of operation and transmission investment cost, increased system security and reliability, increased power transfer capabilities, and an overall enhancement of the quality of the electric energy delivered to customers (IEEE/CIGRÉ, 1995).

1.4 FACTS CONTROLLERS

Power flow control has traditionally relied on generator control, voltage regulation by means of tap-changing and phase-shifting transformers, and reactive power plant compensation switching. Phase-shifting transformers have been used for the purpose of regulating active power in alternating current (AC) transmission networks. In practice, some of them are permanently operated with fixed angles, but in most cases their variable tapping facilities are actually made use of.

Series reactors are used to reduce power flow and short-circuit levels at designated locations of the network. Conversely, series capacitors are used to shorten the electrical length of lines, hence increasing the power flow. In general, series compensation is switched on and off according to load and voltage conditions. For instance, in longitudinal power systems, series capacitive compensation is bypassed during minimum loading in order to avoid transmission line overvoltages due to excessive capacitive effects in the system. Conversely, series capacitive compensation is fully utilised during maximum loading, aiming at increasing the transfer of power without subjecting transmission lines to overloads.

Until recently, these solutions served well the needs of the electricity supply industry. However, deregulation of the industry and difficulties in securing new 'rights of way' have created the momentum for adopting new, radical technological developments based on high-voltage, high-current solid-state controllers (Hingorani and Gyugyi, 2000). A few years ago, in partnership with manufacturers and research organisations, the supply industry embarked on an ambitious programme to develop a new generation of power electronic-based plant components (Song and Johns, 1999). The impact of such developments has already made inroads in all three areas of the business, namely, generation, transmission, and distribution.

Early developments of the FACTS technology were in power electronic versions of the phase-shifting and tap-changing transformers. These controllers together with the electronic series compensator can be considered to belong to the first generation of FACTS equipment. The unified power flow controller, the static compensator, and the interphase power controller are more recent developments. Their control capabilities and intended function are more sophisticated than those of the first wave of FACTS controllers. They may be considered to belong to a second generation of FACTS equipment. Shunt-connected thyristor-switched capacitors and thyristor-controlled reactors, as well as high-voltage direct-current (DC) power converters, have been in existence for many years, although their operational characteristics resemble those of FACTS controllers.

A number of FACTS controllers have been commissioned. Most of them perform a useful role during both steady-state and transient operation, but some are specifically designed to operate only under transient conditions, for instance, Hingorani's subsynchronous resonance (SSR) damper.

FACTS controllers intended for steady-state operation are as follows (IEEE/CIGRÉ, 1995):

- Thyristor-controlled phase shifter (PS): this controller is an electronic phase-shifting transformer adjusted by thyristor switches to provide a rapidly varying phase angle.
- Load tap changer (LTC): this may be considered to be a FACTS controller if the tap changes are controlled by thyristor switches.
- Thyristor-controlled reactor (TCR): this is a shunt-connected, thyristor-controlled reactor, the effective reactance of which is varied in a continuous manner by partial conduction control of the thyristor valve.
- Thyristor-controlled series capacitor (TCSC): this controller consists of a series capacitor paralleled by a thyristor-controlled reactor in order to provide smooth variable series compensation.
- Interphase power controller (IPC): this is a series-connected controller comprising two parallel branches, one inductive and one capacitive, subjected to separate phase-shifted voltage magnitudes. Active power control is set by independent or coordinated adjustment of the two phase-shifting sources and the two variable reactances. Reactive power control is independent of active power.
- Static compensator (STATCOM): this is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus.

- Solid-state series controller (SSSC): this controller is similar to the STATCOM but it is connected in series with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at one of the terminals of the series-connected transformer.
- Unified power flow controller (UPFC): this consists of a static synchronous series compensator (sssc) and a STATCOM, connected in such a way that they share a common DC capacitor. The UPFC, by means of an angularly unconstrained, series voltage injection, is able to control, concurrently or selectively, the transmission line impedance, the nodal voltage magnitude, and the active and reactive power flow through it. It may also provide independently controllable shunt reactive compensation.

Power electronic and control technology have been applied to electric power systems for several decades. HVDC links and static VAR compensators are mature pieces of technology:

- Static VAR compensator (SVC): this is a shunt-connected static source or sink of reactive power.
- High-voltage direct-current (HVDC) link: this is a controller comprising a rectifier station and an inverter station, joined either back-to-back or through a DC cable. The converters can use either conventional thyristors or the new generation of semiconductor devices such as gate turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs).

The application of FACTS controllers to the solution of steady-state operating problems is outlined in Table 1.1.

Table 1.1 The role of FACTS (flexible alternating current transmission systems) controllers in power system operation

Operating problem	Corrective action	FACTS controller
Voltage limits:		
Low voltage at heavy load	Supply reactive power	STATCOM, SVC,
High voltage at low load	Absorb reactive power	STATCOM, SVC, TCR
High voltage following an outage	Absorb reactive power; prevent overload	STATCOM, SVC, TCR
Low voltage following an outage	Supply reactive power; prevent overload	STATCOM, SVC
Thermal limits:		
Transmission circuit overload	Reduce overload	TCSC, SSSC, UPFC, IPC, PS
Tripping of parallel circuits	Limit circuit loading	TCSC, SSSC, UPFC, IPC, PS
Loop flows:		
Parallel line load sharing	Adjust series reactance	IPC, SSSC, UPFC, TCSC, PS
Postfault power flow sharing	Rearrange network or use thermal limit actions	IPC, TCSC, SSSC, UPFC, PS
Power flow direction reversal	Adjust phase angle	IPC, SSSC, UPFC, PS

1.5 STEADY-STATE POWER SYSTEM ANALYSIS

In order to assist power system engineers to assess the impact of FACTS equipment on transmission system performance, it has become necessary to write new power system software or to upgrade existing software (Ambriz-Pérez, 1998; Fuerte-Esquivel, 1997). This has called for the development of a new generation of mathematical models for transmission systems and FACTS controllers, which had to be blended together, coded, and extensively verified. This has been an area of intense research activity, which has given rise to a copious volume of publications. Many aspects of FACTS modelling and simulation have reached maturity, and we believe that the time is ripe for such an important and large volume of information to be put together in a coherent and systematic fashion. This book aims to achieve such a role in the area of steady-state operation of FACTS-upgraded power systems.

From the operational point of view, FACTS technology is concerned with the ability to control, in an adaptive fashion, the path of the power flows throughout the network, where before the advent of FACTS, high-speed control was very restricted. The ability to control the line impedance and the nodal voltage magnitudes and phase angles at both the sending and the receiving ends of key transmission lines, with almost no delay, has significantly increased the transmission capabilities of the network while considerably enhancing the security of the system. In this context, power flow computer programs with FACTS controller modelling capability have been very useful tools for system planners and system operators to evaluate the technical and economical benefits of a wide range of alternative solutions offered by the FACTS technology.

Arguably, power flow analysis – also termed load flow analysis in the parlance of power systems engineers – is the most popular analysis tool used by planning and operation engineers today for the purpose of steady-state power system assessment. The reliable solution of real-life transmission and distribution networks is not a trivial matter, and Newton–Raphson-type methods, with their strong convergence characteristics, have proved most successful (Fuerte-Esquivel, 1997). Extensive research has been carried out over the past 10 years in order to implement FACTS models into Newton–Raphson-type power flow programs. This book offers a thorough grounding on the theory and practice of positive sequence power flow and three-phase power flow. In many practical situations, it is desirable to include economical and operational considerations into the power flow formulation, so that optimal solutions, within constrained solution spaces, can be obtained. This is the object of optimal power flow algorithms (Ambriz-Pérez, 1998), a topic also covered in the book.

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2

Modelling of FACTS Controllers

2.1 INTRODUCTION

Two kinds of emerging power electronics applications in power systems are already well defined: (1) bulk active and reactive power control and (2) power quality improvement (Hingorani and Gyugyi, 2000). The first application area is know as FACTS, where the latest power electronic devices and methods are used to control the high-voltage side of the network electronically (Hingorani, 1993). The second application area is custom power, which focuses on low-voltage distribution and is a technology created in response to reports of poor power quality and reliability of supply affecting factories, offices, and homes. It is expected that when widespread deployment of the technology takes place, the end-user will see tighter voltage regulation, minimum power interruptions, low harmonic voltages, and acceptance of rapidly fluctuating and other nonlinear loads in the vicinity (Hingorani, 1995).

The one-line diagram shown in Figure 2.1 illustrates the connection of power plants in an interconnected transmission system, where the boundary between the high-voltage transmission and the low-voltage distribution is emphasised. The former benefits from the installation of FACTS equipment whereas the latter benefits from the installation of custom power equipment.

To a greater or lesser extent, high-voltage transmission systems are highly meshed. For many decades the trend has been towards interconnection, linking generators and loads into large integrated systems. The motivation has been to take advantage of load diversity, enabling a better utilisation of primary energy resources.

From the outset, interconnection was aided by breakthroughs in high-current, high-power semiconductor valve technology (Arrillaga, 1998). Thyristor-based high-voltage direct-current (HVDC) converter installations provided a means for interconnecting power systems with different operating frequencies – e.g. 50/60 Hz, for interconnecting power systems separated by the sea and for interconnecting weak and strong power systems (Hingorani, 1996). The most recent development in HVDC technology is the HVDC system based on solid-state voltage source converters, which enables independent, fast control of active and reactive powers (McMurray, 1987).

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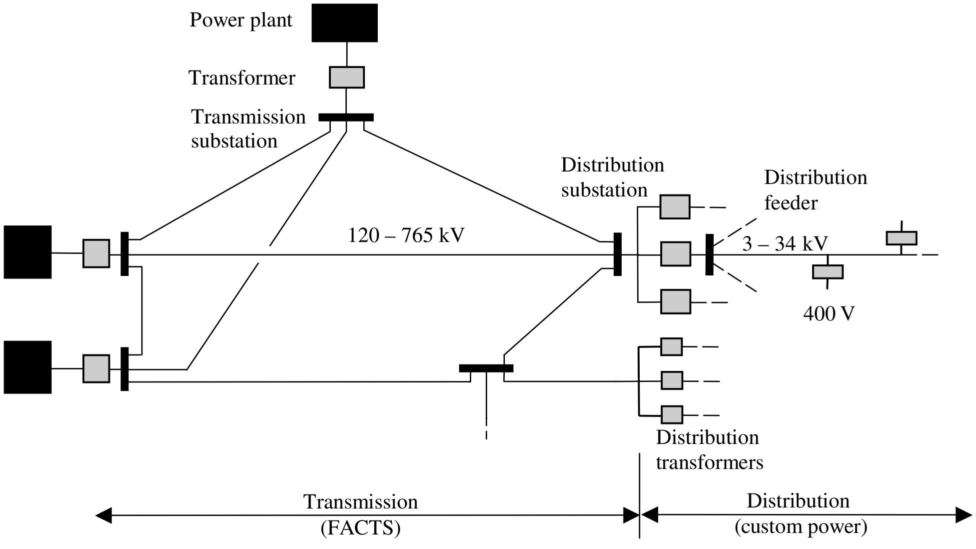

Figure 2.1 A simplified one-line diagram of a power system. Redrawn, with permission, from N.G. Hingorani, 'Introducing Custom Power', *IEEE Spectrum* **32**(6) 41–48, © 1995 IEEE

Power electronics is a ubiquitous technology that has affected every aspect of electrical power networks, not just HVDC transmission but also alternating current (AC) transmission, distribution, and utilisation. Deregulated markets are imposing further demands on generating plants, increasing their wear and tear and the likelihood of generator instabilities of various kinds. To help to alleviate such problems, power electronic controllers have recently been developed to enable generators to operate more reliably in the new marketplace. The thyristor-controlled series compensator (TCSC) is used to mitigate subsynchronous resonances (SSRs) and to damp power system oscillations (Larsen *et al.*, 1992). However, it may be argued that the primary function of the TCSC, like that of its mechanically controlled counterpart, the series capacitor bank, is to reduce the electrical length of the compensated transmission line. Hence, the aim is still to increase power transfers significantly, but with increased transient stability margins. With reference to the schematic network of Figure 2.1, the TCSC is deployed on the FACTS side.

For most practical purposes the thyristor-based static VAR compensator (SVC) has made the rotating synchronous compensator redundant, except where an increase in the short-circuit level is required along with fast-acting reactive power support (Miller, 1982). However, as power electronic technology continues to develop further, the replacement of the SVC by a new breed of static compensators based on the use of voltage source converters (VSCs) is looming. They are known as STATCOMs (static compensators) and provide all the functions that the SVC can provide but at a higher speed (IEEE/CIGRÉ, 1995); it is more compact and requires only a fraction of the land required by an SVC installation. The STATCOM is essentially a VSC interfaced to the AC system through a shunt-connected transformer. The VSC is the basic building block of the new generation of power electronic controllers that have emerged from the FACTS and custom power initiatives (Hingorani and Gyugyi, 2000). In high-voltage transmission, the most popular FACTS equipment are: the STATCOM, the unified power flow controller (UPFC) and the HVDC-VSC. At the low-voltage distribution level, the SVC provides the core of the following custom power equipment: the distribution STATCOM, the dynamic voltage restorer, and active filters.

2.2 MODELLING PHILOSOPHY

The remit of this book is the study of models and procedures with which to assess the steady-state operation of electrical power systems at the fundamental frequency. The power system application tool is termed 'power flows', and the most popular variants of the tool are presented in this book; namely, positive sequence power flow (Stagg and El-Abiad, 1968), optimal power flow (Wood and Wollenberg, 1984), and three-phase power flow (Arrillaga and Arnold, 1990). The first two applications deal with cases of balanced operation, for nonoptimal and optimal solutions, respectively. The third application deals with unbalanced operation induced by imbalances present either in plant components or in system load. In this book, all three applications incorporate representation of conventional power plant components and FACTS controllers.

The modelling of FACTS controllers in both the phase domain and the sequence domain is addressed in this chapter, and Chapter 3 deals with the representation of conventional power plant components in both domains. All models are developed from first principles, with strong reference to the physical structure of the equipment. Such an approach is amenable to flexible models useful for assessing the operation of plant components in network-wide applications, taking due care of equipment design imbalances, which are naturally present in all power plant equipment. However, if such imbalances are small and can be neglected in the study, then simpler models of plant components become readily available, in the form of sequence domain models.

It should be kept in mind that, in this book, the interest is in steady-state analysis at the fundamental frequency, and the models developed reflect this fact. They are not suitable for assessing the periodic steady-state operation of power systems (Acha and Madrigal, 2001) or their dynamic or transient operation (Kundur, 1994).

2.3 CONTROLLERS BASED ON CONVENTIONAL THYRISTORS

Power electronic circuits using conventional thyristors have been widely used in power transmission applications since the early 1970s (Arrillaga, 1998). The first applications took place in the area of HVDC transmission, but shunt reactive power compensation using fast controllable inductors and capacitors soon gained general acceptance (Miller, 1982). More recently, fast-acting series compensators using thyristors have been used to vary the electrical length of key transmission lines, with almost no delay, instead of the classical series capacitor, which is mechanically controlled. In distribution system applications, solid-state transfer switches using thyristors are being used to enhance the reliability of supply to critical customer loads (Anaya-Lara and Acha, 2002).

In this section, the following three thyristor-based controllers receive attention: the thyristor-controlled reactor (TCR), the SVC and the TCSC. The operational characteristic of each one of these controllers is studied with particular reference to steady-state operation.

2.3.1 The Thyristor-controlled Reactor

The main components of the basic TCR are shown in Figure 2.2(a). The controllable element is the antiparallel thyristor pair, Th1 and Th2, which conducts on alternate half-cycles of the supply frequency. The other key component is the linear (air-core) reactor of inductance L (Miller, 1982). The thyristor circuit symbol is shown in Figure 2.2(b).

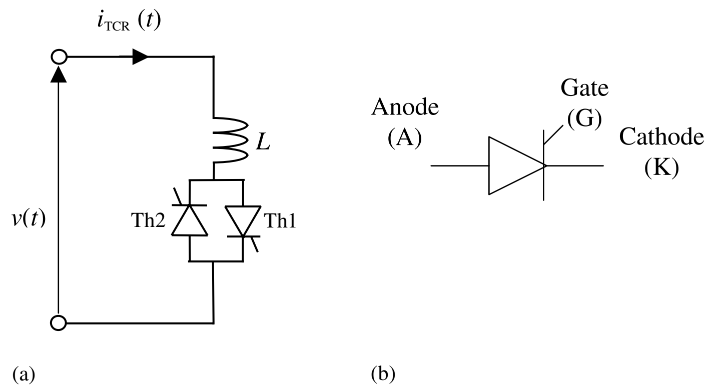

Figure 2.2 Thyristor-based circuit: (a) Basic thyristor-controlled reactor (TCR); (b) thyristor circuit symbol.

The overall action of the thyristor controller on the linear reactor is to enable the reactor to act as a controllable susceptance, in the inductive sense, which is a function of the firing angle α. However, this action is not trouble free, since the TCR achieves its fundamental frequency steady-state operating point at the expense of generating harmonic distortion, except for the condition of full conduction.

First, consider the condition when no harmonic distortion is generated by the TCR, which takes place when the thyristors are gated into conduction, precisely at the peaks of the supply voltage. The reactor conducts fully, and one could think of the thyristor controller as being short-circuited. The reactor contains little resistance and the current is essentially sinusoidal and inductive, lagging the voltage by almost $90°(\pi/2)$. This is illustrated in Figure 2.3(a), where a fundamental frequency period of the voltage and current are shown.

It should be mentioned that this condition corresponds to a firing angle α of $\pi/2$, which is the current zero-crossing measured with reference to the voltage zero-crossing. The relationship between the firing angle α and the conduction angle σ is given by

$$\sigma = 2(\pi - \alpha). \tag{2.1}$$

Partial conduction is achieved with firing angles in the range: $\pi/2 < \alpha < \pi$, in radians. This is illustrated in Figures 2.3(b)–2.3(d), where TCR currents, as a function of the firing angle,