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Flexible AC Transmission Systems: Modelling and Control

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Flexible AC Transmission Systems: Modelling and Control

Foreword

The electric power industry is undergoing the most profound technical, economic and organisational changes since its inception some one hundred years ago. This paradigm change is the result of the liberalisation process, stipulated by politics and followed up by industry. For many years the electric power industry was characterized by a vertically integrated structure, consisting of power generation, transmission/distribution and trading. The liberalisation process has resulted in the unbundling of this organizational structure. Now generation and trading are organised in separate business entities, subject to competition, while the transmission/distribution business remains a natural monopoly. Since the trading of electric energy happens on two levels, the physical level and the contractual level, it has to be recognized that these two levels are completely different. However for understanding the electricity market as a network based industry both levels have to be considered and understood. The fundamental properties of electric energy are as follows:

- Electricity always needs a network for transportation and distribution.
- Electricity cannot be stored in a substantial amount, hence production and consumption have to be matched at each instant of time.
- The physical transport of electricity has nothing to do with the contracts for trading with electricity

The role of the electric network is of prime importance within the electric energy business. Its operation is governed by physical laws. The electric network has a fixed structure consisting of different voltage levels; the higher levels are for transmission purposes whereas the lower levels are used for the distribution tasks. Each network element has a finite capacity, limiting the amount of electricity to be transported or distributed. As a consequence of the liberalisation process the operation of the networks has been pushed closer towards its technical limits. Hence the stress on the system is considerably bigger than in the past. The efficient use of all network elements is of prime interest to the network operator because the cost constraints have also become much tighter than in the past. Recognizing that the operation of a large electric network is a complex and challenging engineering task, it becomes evident that the cost constraints increase the operational complexity considerably. The bigger the interconnected network becomes the more flexibility is required with respect to the cross border trading of electricity. Simultaneously the complexity of operational problems increases due to voltage, angle and frequency stability problems.

The traditional planning approaches for power networks are undergoing a reengineering. The long lasting experience with the power flowing purely from the generation plants to the customers is no longer valid. Growing volatility and increasingly unpredictable system behaviour requires innovative equipment to handle such situations successfully. Keeping in mind that the interconnected power networks have been designed such that each network partner may contribute with reserve power in case of emergency, the trend is now towards extensive cross border energy trading. Another fundamental development is the construction of micro grid on the distribution level. The introduction of dispersed generation close to the customers changes the functionality and the requirements of the distribution networks. The grid operator is requested to provide network access to any interested stakeholder in a transparent and non-discriminatory manner. So, while in the past the power flow in distribution networks was unidirectional, now the system must handle bidirectional power flows. This allows the distribution network to take on more and more the function of a balancing network. At the same time, the capacity of individual elements may not be sufficient to cope with the resulting power flow situations.

Summarizing the current developments, it must be noticed that both planning and operation of electric networks are undergoing fundamental and radical changes in order to cope with the increased complexity of finding economic and reliable network solutions. The operation of the transmission and distribution networks will be closer to their physical limits. The necessity to design electric power networks providing the maximal transmission capacity and at the same time resulting in minimal costs is a great engineering challenge. Innovative operational equipment based on power electronics offers new and powerful solutions. Commonly described by the term 'Flexible AC Transmission Systems' or 'FACTS-devices', such equipment has been available for several years, but has still not been widely accepted by all grid operators for several reasons.

The introduction of innovative equipment has a great impact on the operation. A more flexible transmission or distribution system may cause new problems during normal or disturbed operating states. Furthermore, the proper understanding of innovative equipment is also an educational problem because there is not much experience reported so far with this innovative equipment.

On the other hand, the opportunities for new solutions are substantial and important. FACTS-devices can be utilized to increase the transmission capacity, improve the stability and dynamic behaviour or ensure better power quality in modern power systems. Their main capabilities are reactive power compensation, voltage control and power flow control. Due to their controllable power electronics, FACTS-devices always provide fast control actions in comparison to conventional devices like switched compensation or phase shifting transformers with mechanical on-load tap changers.

This book offers a concise and modern presentation of the timely and important topic of flexible AC transmission networks. There is no doubt that these innovative FACTS-devices will find a definite place in transmission and distribution networks. The complete description of the functionality of such devices is supported with extensive mathematical models, which are required when planning the use of this type of equipment in electrical networks. The first part of the book deals with the modeling of single and multi-converter FACTS-devices in single and three-phase power flow studies and optimal power flow solutions.

The in depth discussion of the operational and controlling aspects in the second part of the book makes it a most valuable compendium for the design of future electric networks. Without a complete and powerful solution of the control problems, the FACTS-devices will not find their application in power systems because they have to operate in normal and contingency situations in a reliable and economic way. System security must not be weakened by the FACTS-devices, even if the system is operated closer to its limits. The control speed of the FACTS-devices can only be utilized, if they are first given higher priority from the operator, then designed to react in a coordinated but autonomous manner in dynamic or even contingency situations. A novel and original control strategy based on the autonomous control theory fulfilling these requirements is presented in the book.

Due to the influence of FACTS-devices on wide system areas, especially for power flow and damping control, an exchange of system information with the FACTS-controllers is required. A wide area control scheme is introduced and applied for power flow control. The dynamics of FACTS-devices provide effective damping capability. Inter-area oscillations require wide area system supervision and a wide area control scheme. For this application time delays in the wide area control loop play a significant role in the controller design. Based on detailed modeling, an innovative approach is presented considering this time delay, making wide area damping control feasible. Only with such a control scheme, FACTS-devices can be applied beneficially in the future.

Based on the authors' extensive experience, this book is of greatest importance for the practical power engineers for both planning and operational problems. It provides a deep insight into the use of FACTS-devices in modern power systems. Although the technology of modern power electronics will change very quickly, the results presented in this book are sustainable and long lasting. The combination of theoretical and practical knowledge from the international team of authors from academia and industry provides an invaluable contribution for the future application of FACTS-devices. I am convinced that this book will become a standard work in modern power engineering. It will serve equally as a text book for university students as well as an engineering reference for planning and operation of modern power systems.

Dortmund, Germany, 2005 / 2012 Prof. Dr.-Ing. Edmund Handschin

Preface

Electricity market activities and a growing demand for electricity have led to heavily stressed power systems. This requires operation of the networks closer to their stability limits. Power system operation is affected by stability related problems, leading to unpredictable system behavior. Cost efficient solutions are preferred over network extensions. In many countries, permits to build new transmission lines are hard to get, which means the existing network has to be enforced to fulfill the changing requirements.

Power electronic network controllers, the so called FACTS-devices, are well known having several years documented use in practice and research. Several kinds of FACTS-devices have been developed. Some of them such as the Thyristor based Static Var Compensator (SVC) are a widely applied technology; others like the Voltage Source Converter (VSC) based Static Compensator (STATCOM) or the VSC-HVDC are being used in a growing number of installations worldwide. The most versatile FACTS-devices, such as Unified Power Flow Controller (UPFC), although still confined primarily to research and development applications, have the potential to be used widely beyond today's pilot installations.

In general, FACTS-devices can be utilized to increase the transmission capacity, the stability margin and dynamic behavior or serve to ensure improved power quality. Their main capabilities are reactive power compensation, voltage control and power flow control. Due to their controllable power electronics, FACTS-device provide always a fast controllability in comparison to conventional devices like switched compensation or phase shifting transformers. Different control options provide a high flexibility and lead to multi-functional devices.

To explore the capabilities of FACTS-devices, a specific operation and control scheme has to be designed. Fundamental to their operation and control is their proper modeling for static and dynamic purposes. The integration of FACTS-devices into basic tools like power flow calculation and optimal power flow (OPF) is mandatory for a beneficial system operation. Due to the wide area and dynamic impact of FACTS-devices, a pure local control is desired, but is not sufficient in many cases. The requirements for normal and emergency operation have to be defined carefully. A specific control design has to address these different operational conditions. This book introduces the latest results of research and practice for modeling and control of existing and newly introduced FACTS-devices.

Motivation

This book is motivated by the recent developments of FACTS-devices. Numerous types of FACTS-devices have been successfully applied in practical operation. Some are still in the pilot stage and many are proposed in research and development. From practical experience it has been seen that the investment into FACTS-devices, in most of the cases, only pays off by considering their multi-functional capabilities, particularly in normal and emergency situations. This requires a three-phase modeling and a control design addressing both normal and emergency conditions which, in most of the cases, uses wide area information. The recent results and requirements for both modeling and control have motivated this book.

Focus and Target

The focus and target of this book is to emphasize advanced modeling, analysis and control techniques of FACTS. These topics reflect the recent research and development of FACTS-devices, and foresee the future applications of FACTS in power systems. The book comprehensively covers a range of power system control problems like steady state voltage and power flow control, voltage and reactive power control, voltage stability control and small signal stability control using FACTS-devices.

Beside the more mature FACTS-devices for shunt compensation, like SVC and STATCOM, and series compensation, like TCSC and SSSC, the modeling of the latest FACTS-devices for power flow control, compensation and power quality (IPFC, GUPFC, VSC HVDC and Multi-VSC-HVDC, etc.) is considered for power system analysis. The selection is evaluated by their actual and future practical relevance. The multi-control functional models of FACTS-devices and the ability for handling various internal and external operating constraints of FACTS are introduced. In addition, models are proposed to deal with small or zero impedances in the voltage source converter (VSC) based FACTS-devices. The FACTS-device models are implemented in power flow and optimal power flow (OPF) calculations. The power flow and OPF algorithms cover both single-phase models and especially three-phase models. Furthermore the unbalanced continuation power flow with FACTS is presented.

The control of FACTS-devices has to follow their multi-functional capabilities in normal and emergency situations. The investment into FACTS is normally justified by the increase of stability and primarily by the increase of transmission capability. Applications of FACTS in power system operation and control, such as transfer capability enhancement and congestion management, are used to show the practical benefits of FACTS devices.

A comprehensive FACTS-control approach is introduced based on the requirements and specifications derived from practical experience. The control structure is characterised by an autonomous system structure allowing, as far as possible, control decisions to be taken locally, but also incorporating system wide information where this is required. Wide Area Measurement System (WAMS) based control methodologies, which have been developed recently, are introduced for the first time in a book. In particular, the real-time control technologies based on Wide Area

Measurement are presented. The current applications and future developments of the Wide Area Measurement based control methodologies are also discussed. As a particular control topic, utilizing the control speed of FACTS-devices, a special scheme for small-signal stability and damping of inter-area oscillations is introduced. Advanced control design techniques for power systems with FACTS including eigenvalue analysis, damping control design by the state-of-the art Linear Matrix Inequalities (LMI) approach and multiple damping controller coordination is presented. In addition, the time-delay of wide area communications, which is required for a system wide damping control, is considered.

These aspects make the book unique in its area and differentiate from other books on the similar topic. The work presented is derived both from scientific research and industrial development, in which the authors have been heavily involved. The book is well timed, addressing current challenges and concerns faced by the power engineering professionals both in industries and academia. It covers a broad practical range of power system operation, planning and control problems.

Structure

The first chapter of the book gives an introduction into nowadays FACTS-devices. Power semiconductors and converter structures are introduced. The basic designs of major FACTS-devices are presented and discussed from a practical point of view. The further chapters are logically separated into a modeling and a control part. The modeling part introduces the modeling of single and multi-converter FACTS-devices for power flow calculations (Chapter 2 and 3) and optimal power flow calculations (Chapter 4). The extension to three phase models is given in chapter 5. This is fundamental for proper system integration for steady state balanced and unbalanced voltage stability control or the increase of available transmission capacity.

Chapter 6 and 7 present the steady state voltage stability analysis for balanced and unbalanced systems. The increase of transmission capacity and loss reduction with power flow controlling FACTS-devices is introduced in chapter 8 along with the financial benefits of FACTS. From these results it can be seen, that the benefits of FACTS can be increased by utilizing the fast controllability of FACTS together with a certain wide area control scheme.

The control part of the book starts with chapter 9 introducing a non-intrusive system control scheme for normal and emergency situations. The chapter takes the view, that a FACTS-device should never weaken the system stability. Based on this condition, the requirements and basic control scheme for FACTS-devices are derived. Chapter 10 introduces an autonomous control system approach for FACTS-control, balancing the use of local and global system information and considering normal and emergency situations. Due to the influence of FACTS-devices on wide system areas, especially for power flow and damping control, an exchange of information with the FACTS controllers is required. A wide area control scheme for power flow control is introduced in chapter 11. The benefits of power flow control can be achieved only with wide area system information.

The control options available with FACTS-devices can provide effective damping capability. Chapter 12 and 13 (chapter 13 and 14 in 2nd edition) deal with small signal stability and the damping of oscillations, which is a specific application area utilizing the control speed of FACTS. The coordination of several FACTS damping controllers requires a formally introduced wide area control scheme. This approach has to consider communication time delays carefully, which is a specific topic of chapter 13.

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University of Warwick, Coventry, UK, 2005 — Xiao-Ping Zhang
ABB China Ltd, Beijing, China, 2005 — Christian Rehtanz
Imperial College London, London, UK, 2005 — Bikash Pal

Preface to Second Edition

In the six years since we published the first edition of this book research on the FACTS has continued to flourish while renewable energy has developed into a mature and booming global green business. With the increasing amount of renewable energy and its volatility, the demand for flexible network operation and control is growing significantly.

The second edition reflects the new developments in converter configuration, smart grid technologies, super power grid developments worldwide, new approaches for FACTS control design, new controllers for distribution system control, and power electronic controllers in wind generation operation and control, etc. It should be mentioned that with the voltage sourced converter technologies, FACTS and HVDC demonstrate similar operation and control features while the differences between them become small.

The Changes and New Chapters

Some changes and updates have been made to the original chapters. Especially in chapter 1, the latest trends of VSC-HVDC with multilevel architecture have been included.

In addition to the above changes, four new chapters are added into the second edition of this book. The previous chapters 11, 12 and 13 from the 1st edition are now chapters 12, 13 and 14.

- New Chapter 11 targets on a multi-agent approach for an automated coordination and control of power flow control devices. The approach is fully distributed and does not require any central instance for the topology analysis. The agents derive the relevant actual topology through local communication and perform coordinated control actions according to the present situation. Therefore the approach can be implemented easily under the condition that a fast communication network between all network elements is available.
- Chapter 15 discusses the design of a FACTS damping controller that can achieve satisfactory performance over several operating conditions. Basically the nonlinear power system model is linearized around these operating conditions, a set of linearized state equations can formulate the multi-model system. So in principle the control design for the system with several operating points is to design a common controller for the multi-model system. However, the output feedback problem of a multi-model system is now described by the nonlinear matrix inequalities (NMI). A two-step LMI based approach is proposed to design an output feedback controller for a multi-model system – NMI problem where the pole placement of the closed-loop system is considered.

- Chapter 16 presents the Loop Power Controller (LPC) for distribution systems. The device can achieve various power quality improvements such as system voltage control when incorporating distributed generation (DG), balancing control of distribution feeder loadings and high speed compensation of voltage sags. It should be mentioned the LPC is a promising device to form loop distribution systems without increasing short-circuit current.
- Chapter 17 presents mathematical models for wind turbines such as wind turbine (WT) with doubly fed induction generator (DFIG) and WT with direct-drive permanent magnet generator (DDPMG), discusses small signal stability analysis and nonlinear control using power electronic back-to-back converters, which are very similar to those of UPFC and VSC HVDC. In addition, dynamic equivalent modeling of wind farms and wind farm interconnection with power grid via VSC HVDC are covered.

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