INTRODUCTION TO FACTS CONTROLLERS

Theory, Modeling, and Applications

Kalyan K. Sen
Mey Ling Sen

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To our family, friends,
and all our gurus who brought us to this point

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About the Authors

FOREWORD

This book is an outgrowth of two decades of the authors' engineering experience with flexible AC transmission systems (FACTS) design. Today, more than ever before, we are faced with problems of grid congestion and the limitations of power flow in electric power transmission systems. As an integral part of the grid modernization, all alternatives that allow for increased power flow are being explored. FACTS controllers represent the latest and one of the most important technological advances in recent years. It is an emerging field that will require, in the near future, significant research and development. I am convinced that the FACTS controllers will penetrate the high-voltage transmission systems and spread to applications in medium-voltage distribution networks.

Utilities need better modeling techniques for FACTS controllers to use in their system studies. More than anything else, power engineers need to have a basic understanding of the FACTS controllers. When alternatives are considered, the FACTS controllers must be compared from the technical as well as the economical viewpoints.

The book covers a wide area of development and applications of FACTS controllers and is unique in many ways in that it

- Provides the basic theory and the step-by-step evolution to understand FACTS controllers
- Offers modeling techniques that are so essential to electric utilities when conducting their system studies
- Provides computer codes for the FACTS controllers
- Describes a new class of FACTS controllers based on the transformer technology proposed by the authors and named Sen transformer

The topic is of great interest to many utility engineers, large power equipment manufacturers, university professors, and students. The book should benefit all power engineering professionals who want to stay abreast of the evolution of the FACTS technology and associated power electronics. There is no other book that helps a reader to actually "do something" in the field, the way this one does. I believe this book demystifies many of the topics discussed.

In summary, the subject of "FACTS Controllers" cannot be overstressed; it is a very important topic in the electric power industry and electric utilities, particularly in today's environment. Due to the current deregulation trend, the aging of transmission components, the need to reduce costs of operations, the need to ensure reliability of power flow, and the need to achieve efficient transmission utilization, electric utilities will seriously consider all alternatives, including FACTS controllers to improve the power flow along the transmission lines. This is a timely book in the beautiful field of power electronics; it is an advanced application-oriented manual that gives the reader clear instructions on how to model, design, build, evaluate, and install FACTS controllers. It supplements nicely the very few existing books. I realize that this is the first FACTS book that is practical, hands-on, and a true guide for the practicing engineers. I think the authors have an excellent feeling for the prospective readers. The book gives significant amounts of detail in modeling and presentation that will be much appreciated by researchers/engineers in the field. This book is a cornucopia of practical information that is missing in the existing engineering literature.

I have read this book with great satisfaction. It is a work of love, written by two spouses who are former students of Worcester Polytechnic Institute. Kalyan Sen was my Ph.D. student. This book reminds me of the words of Henri Frederic Amiel: "The highest function of the teacher consists not so much in imparting knowledge as in stimulating the pupil in its love and pursuit."

ALEXANDER E. EMANUEL
D.Sc., P.E., Life Fellow, IEEE

Worcester, Massachusetts
January 2009

PREFACE

Both authors have been involved in exploring flexible AC transmission systems (FACTS) controllers since the early 1990s. Kalyan Sen developed VSC-based FACTS models while working at Westinghouse. He has written an award-winning technical committee paper on the modeling of UPFC in the *IEEE Transactions on Power Delivery*. Mey Ling Sen explored an alternate approach to VSC-based FACTS controllers that is cost effective for most utility applications. This effort led to the concept of the Sen transformer (ST). She has modeled all kinds of FACTS controllers in great detail.

Since 2002, Kalyan Sen has traveled around the world as an IEEE Distinguished Lecturer, speaking in more than 30 places. When he gives a presentation on FACTS controllers, his approach is to start from the basics and lead up to the advanced concept of VSC-based FACTS controllers and the ST. His emphasis is based on real-world experience in modeling, simulation, design, and commissioning. He was requested in many places to compile his lecture material in the form of a book. A considerable amount of effort has been put into modeling FACTS controllers. Modeling is the only approach, before any hardware construction, for the verification of the performance of any concept. The book includes some of the major FACTS controllers' models in EMTP.

The book is divided into nine chapters and three appendices. Chapter 1 explains the origin of modern FACTS controllers and guides the reader to the selection process of the right FACTS controller.

Chapter 2 is for anyone who would like to be familiar with the subject and use the book as a reference. It explains various topics of the book in simple engineering terms and corroborates the theory with relevant mathematics. The characteristics of various FACTS controllers, shown from the derived formulae, are verified with detailed simulation in the subsequent chapters.

Chapter 3 gives the "nuts and bolts" of modeling in EMTP and explains the basic differences of modeling various FACTS controllers, such as the voltage regulating transformer (VRT), phase angle regulator (PAR), unified power flow controller (UPFC), and the ST.

Chapter 4 describes the transformer-based FACTS controllers and sets some baselines for comparison with power electronic types in the following chapters.

Chapter 5 describes some early FACTS controllers that use mechanical switches and sets some baselines for comparison in the following chapters.

Chapter 6 describes the heart of the voltage-sourced converter (VSC) using harmonic neutralized (HN) techniques. It also briefly describes other approaches.

Chapter 7 shows intricate modeling and analysis of the basic building block of a VSC—a two-level pole. This chapter may be of interest to those who are interested in switch design. The analysis technique is applicable to other semiconductor switches as well.

Chapter 8 presents the modeling techniques and control implementations of the three basic VSC-based FACTS controllers: shunt-connected static synchronous compensator (STATCOM), series-connected static synchronous series compensator (SSSC), and shunt-series-connected UPFC. A comparison of simulation and field results is presented. The protection strategy of VSC-based FACTS controllers is discussed.

Chapter 9 presents the motive and evolution of the ST and its wide variety of applications.

Appendix A covers the operation of various items, such as (a) three-phase balanced and unbalanced voltage, current, and power; (b) symmetrical components; (c) d–q transformation; and (d) Fourier analysis. The reader will find it useful to see industry techniques and the relevance of theory and applications.

Appendix B presents the power flow control equations in a lossy transmission line and compares the derived results from those in Chapter 2 for lossless lines.

Appendix C presents the sample models that are discussed in this book. However, a more comprehensive set of models is available at the following ftp address:

ftp://ftp.wiley.com/public/sci_tech_med/facts_controllers

Color representations of the figures of the book can be downloaded from the same ftp address.

The Bibliography includes some books and reports and more than 160 technical papers.

KALYAN K. SEN
MEY LING SEN

Pittsburgh, Pennsylvania
January 2009

ACKNOWLEDGMENTS

We both would like to thank our colleagues at Westinghouse where the pioneering development of FACTS controllers took place. We also appreciate our brief time spent in Sweden with our fine colleagues at ABB. We are very grateful for all those who dedicated their time to review the manuscript thoroughly and provide valuable feedback. We thank Prof. Venkata Dinavahi for identifying various references. We appreciate feedback from our readers. Our email addresses are senkk@ieee.org and senml@ieee.org, respectively.

K. K. S.
M. L. S.

Very special thanks go to my two mentors at Westinghouse—Theodore Heinrich and Michael Brennen who are heroes of the power electronics industry. Proper thanks go to Dr. Laszlo Gyugyi who convinced me to change my job from academia to industry, a change that I never regretted.

Throughout my tenure at Westinghouse Science & Technology Center in Pittsburgh, I had a rare opportunity of working with extraordinary people from all over the world. Not only were they a fine class of engineers, they also had hobbies that could be considered as careers in their own rights. During the long hours of commissioning of the world's first UPFC in Kentucky, and a STATCOM in Texas, the team of engineers kept everyone amused with their life stories. I thank the fine colleagues at the Tennessee Valley Authority, American Electric Power, New York Power Authority, Bonneville Power Administration, Western Area Power Administration, and the Electric Power Research Institute.

K. K. S.

NOMENCLATURE

α	Relative phase angle of the shunt-connected compensating voltage
β	Relative phase angle of the series-connected compensating voltage
γ	“Dead” angle of a three-level voltage-sourced converter (VSC) when the output voltage is zero
δ	Power angle (difference of phase angles of the voltages at the two ends of a transmission line)
ε	Least error of the calculated voltage and actually tapped voltage in the Sen transformer
θ	Phase-locked loop (PLL) angle
°	degree
ϕ	Power factor angle
ω	Angular frequency
ψ	Angle between the voltages at the modified sending end and the sending end of a line
ζ	Dynamic angle of the series-connected VSC
Ω	Unit of resistance, reactance, and impedance
A	Ampere (unit of current)
BTB-SSSC	Back-to-back SSSC
BTB-STATCOM	Back-to-back STATCOM
BYPBRK	Bypass breaker
C	Capacitance
cos (ϕ)	Power factor
cp	Compensating points in the Sen transformer
CSC	Current-sourced converter
DCLS	DC link switch
$Di_{G(Tfall)}$	Slope of i_G at the midpoint of T_{fall}
$Di_{G(Ttail)}$	Slope of i_G at the midpoint of T_{tail}
E	Compensating voltage behind a tie reactance
ES	Electronic switch
F	Farad (unit of capacitance)
GPFC	Generalized power flow controller
GST	Generalized Sen transformer

H	Henry (unit of inductance)
Hz	Hertz (unit of frequency)
i	Instantaneous current
$\mathbf{I}$	Phasor current
IPFC	Interline power flow controller
I_m	Peak reverse current
I_O	Forward conducting current of a VSC pole
K	Ratio of the GTO currents at the end of T_{fall} to that at the beginning of T_{fall}
L	Inductance
LTC	Load tap changer
MC	Magnetic circuit
MST	Multiline Sen transformer
Mvar	Mega VAR (unit of reactive power)
p	Three-phase instantaneous active power
P	Active power
PAR	Phase angle regulator
PFC	Power flow controller
PST	Phase shifting transformer
q	Three-phase instantaneous quadrature power
Q	Quality factor
Q	Reactive power
Q_a	Reverse recovery charge
r_k	Voltage error at a possible *k*th operating point in the Sen transformer
R	Resistance
$_{\mathrm{r}}$	Receiving end
S	Apparent power
$_{\mathrm{s}}$	Sending end
$_{\mathrm{s'}}$	Modified sending end
SSSC	Static synchronous series compensator
ST	Sen transformer
STATCOM	Static synchronous compensator
SVC	Static var compensator
t	Time
TCR	Thyristor-controlled reactor
T_{fall}	GTO current fall time
THD	Total harmonic distortion
t_{ON}	Turn-on time of a GTO
TSC	Thyristor-switched capacitor
T_{tail}	GTO current tail time
X	Reactance
UPFC	Unified power flow controller
v	Instantaneous voltage
$\mathbf{V}$	Phasor voltage

V	Volt (unit of voltage)
VA	Volt-ampere (unit of apparent power)
VAR	Volt-ampere reactive (unit of reactive power)
v_B	Forward blocking voltage of a GTO
VRT	Voltage regulating transformer
VSC	Voltage-sourced converter
$\mathbf{V}_{\mathbf{s}'\mathbf{s}}$	Series compensating voltage
W	Watt (unit of active power)

1

APPLICATIONS OF FACTS CONTROLLERS

The locations for electricity generation are based on the presence of energy sources, availability of land for new power plants or substations, need for power in a given area, and availability of a transmission network. Electrical energy is transported from the generating point to the point of use through interconnected transmission lines as shown in Figure 1-1. The flow of electricity takes place freely through the path of least impedance and this natural flow of electricity may cause certain transmission lines to be overloaded or underloaded. The flow of electricity in a particular line of a transmission system can be controlled with the use of a power flow controller (PFC), as shown in Figure 1-2.

The demand for electrical energy around the world increases continuously. The ever-growing need for transporting more electricity can be met either by installing new transmission lines or by using the existing ones in a more efficient way. The construction of new transmission lines is increasingly difficult because of various reasons, such as regulatory, environmental, and public policies, as well as the escalating cost. The free flow of electricity from one particular point to another might not take the shortest path. Any unwanted path along the way causes extra power loss, loop flow of power, and reduced stability with increased voltage variation in the line. In the present environment, the power industry is in constant search for the most economic ways to transfer bulk power along a desired path. Before considering new transmission lines, it is

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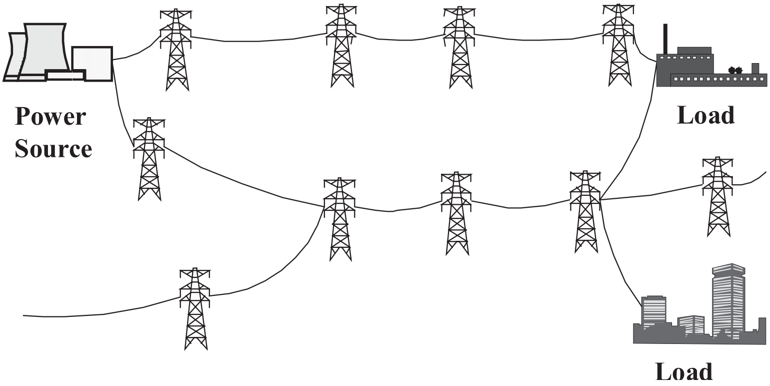


Figure 1-1. Part of a large interconnected transmission system supplying electric power from the generating point to the loads.

desirable to explore other ways to increase the usage of existing transmission lines by increasing their power flow.

The flow of electric power has two components: active power and reactive power. A transmission line consists of electrical conductors that have resistance, inductance, and capacitance. The active power, except for the loss in the resistance of the conductor, reaches from one end of the line to the other. This active power can be converted into lighting, heating, motion force in electric motors, and so on, generating revenue. The inherent inductive and capacitive reactances of the conductor absorb and generate reactive power. This reactive power flow causes an extra loss in the resistance of the conductor.

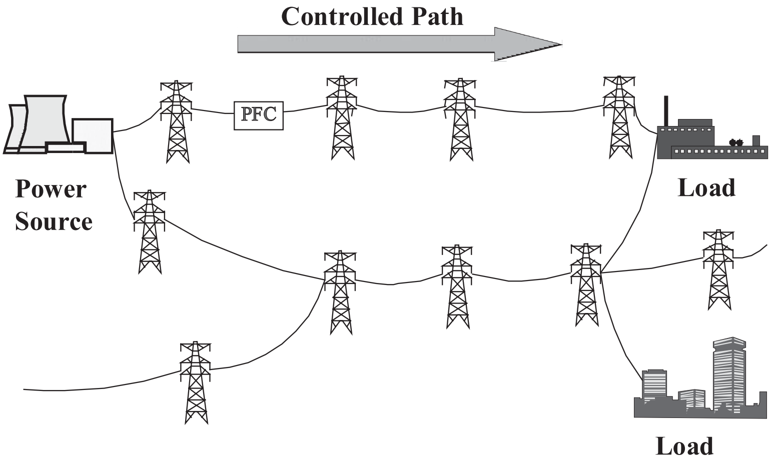


Figure 1-2. Power flow along a controlled path.

The natural or uncompensated power flow through a transmission line in a power network is, in general, not economically optimal. The natural active and reactive power flows (P_{rn} and Q_{rn}) at the receiving end are

$$P_{rn} = \frac{V_s V_r}{X} \sin(\delta_s - \delta_r)$$

and

$$Q_{rn} = \frac{V_s V_r}{X} \left\{ \cos(\delta_s - \delta_r) - \frac{V_r}{V_s} \right\}$$

where the magnitudes of the voltages at the sending and receiving ends are V_s and V_r, the corresponding phase angles are δ_s and δ_r, and the line reactance is X. The power flow control parameters are voltage magnitudes, their phase angles, and line reactance. Any of these parameters can be controlled with the use of the following, now considered conventional, equipment:

- Voltage regulating transformer (VRT), shunt or parallel-connected switched inductor/capacitor, static var compensator (SVC), or static synchronous compensator (STATCOM) for voltage regulation, as shown in Figure 1-3
- Phase angle regulator (PAR) or phase shifting transformer (PST) for phase angle regulation, as shown in Figure 1-4
- Thyristor-controlled series capacitor (TCSC) for series reactance regulation, as shown in Figure 1-5

For more than a century, the transmission line voltage has been regulated with transformers and tap changers. They are referred to in this book as the VRT in the form of a two-winding transformer with isolated windings and an autotransformer with electrical connection between the windings. In both transformers, the line voltage is applied to the primary windings. In the two-winding transformer, the full line voltage is induced in the secondary windings, whereas, in the autotransformer, only a fraction of the line voltage is induced in the secondary windings that are connected to the primary windings to produce the full line voltage. In both cases, the magnitude of the line voltage is regulated. The secondary voltage is varied with the use of load tap changers (LTCs). An LTC can step up/down the voltage without interruption of the load current. Both primary and secondary windings in the two-winding transformer carry the full transmitted power. Both primary and secondary windings in the autotransformer carry only a fraction of the full transmitted power. The indirect way to regulate the line voltage is to connect an inductor or a capacitor in shunt with the transmission line. A shunt-connected inductor absorbs reactive power from the line and lowers the line voltage, whereas a shunt-connected capacitor raises the line voltage with its generated reactive power. The SVC connects fixed capacitors in a step-like manner in shunt with the line through thyristor switches and also connects an inductor in shunt with the line through thyristor switches whose duty cycle can be varied, thereby making it function

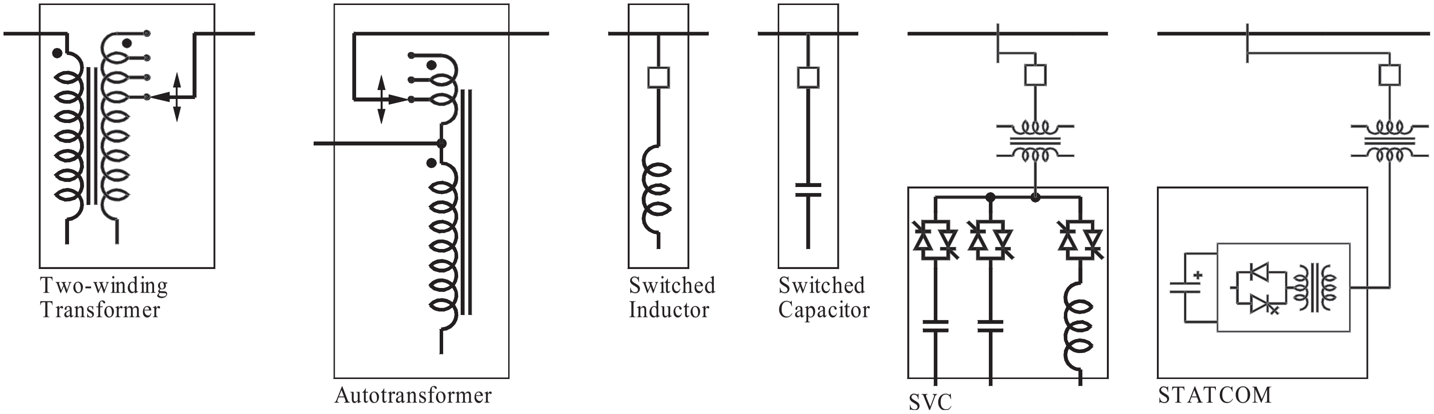


Figure 1-3. Transmission line voltage regulators.

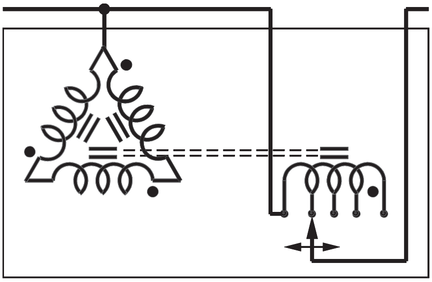


Figure 1-4. Transmission line voltage phase angle regulator.

as a variable inductor. The indirect way to regulate the shunt-connected inductor or capacitor is to use a voltage-sourced converter (VSC)-based STATCOM that connects an electronically generated sinusoidal voltage (with some harmonic components) in shunt with the transmission line through a tie inductor. The same concept has been practiced with the use of a synchronous condenser. The power flow in a transmission line has also been regulated with the use of the PAR. The line voltage is applied to the primary windings and the induced secondary voltage that is varied with the use of LTCs is connected in series with the line. Through the use of the TCSC, a series-connected variable capacitor or a variable inductor can be implemented. As a result, both the magnitude and the phase angle of the line voltage are varied simultaneously.

In a lightly loaded transmission line, the reactive power absorbed by the line inductance becomes much less in comparison to the reactive power generated by the line capacitance. The resulting voltage increase in the line may reach or exceed the allowable limits for the system equipment. In a heavily loaded transmission line, the reactive power needed by the line inductance becomes much more in comparison to the reactive power generated by the line capacitance. The resulting voltage along the line may decrease to a point that is below an acceptable limit. If the voltage along the transmission line is increased to be regulated at its nominal value by using a voltage regulator, the active power flow increases over the natural flow. If the phase angle between the voltages at the two ends of the transmission line is increased by using the PAR, the active power flow also increases. The unintended consequence of increasing active power flow by voltage regulation or phase angle regulation is that the reactive power flow

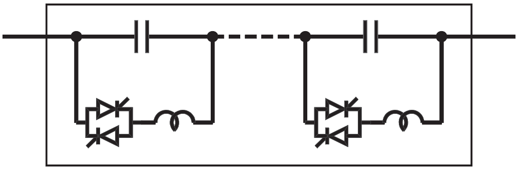


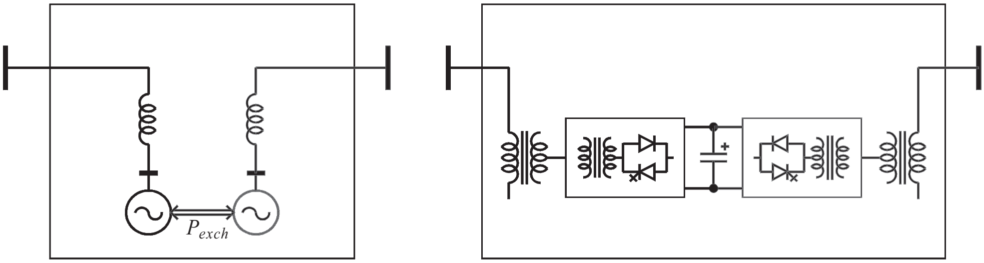
Figure 1-5. Thyristor-controlled series capacitor for transmission line reactance regulation.

in the line is also affected. When the line reactance is regulated, both the active and reactive power flows in the transmission line are varied simultaneously.

If the reactive power along the line is reduced, the freed-up capacity of the line can be used to increase the flow of active power. As a consequence, the generator will be required to supply less reactive power. Furthermore, the efficiencies of the generators and step-up transformers under this condition also increase. In the final analysis, the transmission line needs to be compensated to operate under independent, not simultaneous, control of the active and reactive power flows, so that the line can facilitate the delivery of active power with the greatest value. The active and reactive power flows in a transmission line can be regulated independently by recently developed PFCs that control both the magnitude and phase angle of the transmission line voltage independently.

The magnitude and phase angle of the transmission line voltage can be controlled independently by a shunt-connected compensating voltage, using a shunt–shunt power converter, as shown in Figure 1-6. This concept dates back to the time when rectifiers and inverters were introduced to convert AC power from one voltage and frequency level to another with active power (P_{exch}) transfer through a DC link. The most frequently used topology is an AC-to-DC rectifier followed by a DC-to-AC inverter for variable speed motor drives and, if combined with local energy storage, an uninterruptible AC power supply. To improve the power quality at the rectifier's AC terminal and to accomplish a bidirectional power flow, two DC-to-AC inverters are connected back to back via their DC links, as shown in the figure. This configuration in electric utility applications is known as a back-to-back static synchronous compensator (BTB-STATCOM).

The transfer of power from one line to another can be achieved with the use of a BTB-STATCOM that consists of at least two VSCs, each of which is connected in shunt (parallel) with the transmission line through a coupling transformer. All the VSCs are connected at their shared DC link. The shunt-connected compensating voltage is of variable magnitude and phase angle, and it is also at any phase angle with the prevailing line current. Accordingly, it exchanges active and reactive powers with the line. The exchanged active power flows bidirectionally through the shared link. Each



Shunt–Shunt Power Converter

Back-to-Back STATCOM

Figure 1-6. Point-to-point transfer of power with local reactive power compensation using a shunt–shunt power converter (BTB-STATCOM).