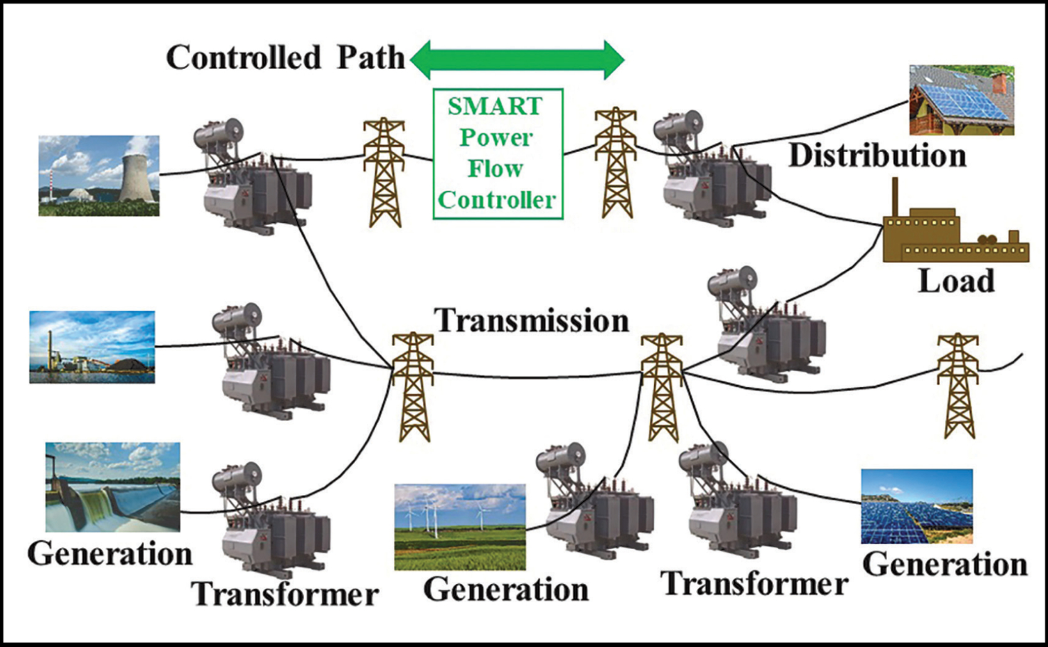
Power Flow Control Solutions for a Modern Grid using SMART Power Flow Controllers



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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Authors' Biographies

Kalyan K. Sen was born in Bankura, West Bengal, India. He received BEE (first class honors, 1982), MSEE (1983), and PhD degrees (1987), all in Electrical Engineering, from *Jadavpur University* (India), *Tuskegee University* (USA), and *Worcester Polytechnic Institute* (USA), respectively. He also received an MBA (2012) from *Robert Morris University* (USA). He is the President and Chief Technology Officer of Sen Engineering Solutions, Inc. (www.sentransformer.com). From 1987 to 1990, he was an Assistant Professor at Prairie View A&M University. From 1990 to 2020, he worked mostly at Westinghouse and its successor companies in the United States, except during 1999–2001 when he worked at ABB in Sweden. He was a key member of the Flexible Alternating Current Transmission Systems (FACTS) development team at Westinghouse Science & Technology Center for which he became a Westinghouse Fellow Engineer. He contributed to the concept development, simulation, design, and commissioning of FACTS projects at Westinghouse since their inceptions in the 1990s. He conceived some of the basic concepts in power flow control technology for which he was elevated to the Institute of Electrical and Electronics Engineers (IEEE) Fellow grade with the citation: **for the development and application of power flow control technology**.

Kalyan has authored or coauthored more than 25 peer-reviewed publications, 8 issued patents, 2 books, and 3 book chapters in the areas of power flow control and power electronics. He is the coauthor of the book titled, *Introduction to FACTS Controllers: Theory, Modeling, and Applications*, IEEE Press and John Wiley & Sons, Inc. 2009, which is also published in Chinese and Indian (English) paperback editions. This book is used in universities and industries worldwide. His interests are in power converters, control systems, electrical machines, and power system simulations and studies. He is a licensed Professional Engineer in Pennsylvania and New York. He also served as a Fulbright Specialist (sponsored by the U.S. Government) and Global Initiative of Academic Networks (GIAN) Scholar (sponsored by the Government of India). He is an individual member of CIGRE.

Kalyan has served many organizations. He has been serving as an IEEE Power & Energy Society (PES) Distinguished Lecturer since 2002. In that capacity, he has given presentations on power flow control technology more than 150 times in 15 countries. He is an AdCom Member of the Power Electronics Society (PELS) and serves as the PELS Regions 1-6 Chair. He is the IEEE Division II Representative to the Board of Governors of Society on Social Implications of Technology (SSIT) and serves as the Chapters Committee Chair. He also serves as the Chair of IEEE Pittsburgh SSIT

Chapter. In 2003, he reestablished the Pittsburgh Chapters of the PES and the Industry Applications Society (IAS). Both Chapters received the "Outstanding Large Chapter" awards for their activities in 2004. He served as the Founding Chair of IEEE Pittsburgh PELS Chapter that received the Best Chapter Award in 2015. Under his Chairmanship, the IEEE Pittsburgh Section received the "Outstanding Large Section" award for its activities in 2005. He served as an Editor of the *IEEE Transactions on Power Delivery* from 2002 to 2007. He served as the Technical Program Chair of the 2008 PES General Meeting in Pittsburgh, and the Chapters and Sections Activities Track Chair at the 2008 IEEE Sections Congress in Quebec City, Canada. He has served as the Special Events Chair of the IEEE Pittsburgh Section for a decade. He received the IEEE Pittsburgh Section **Outstanding Volunteer Service** Award and Power & Energy Society **Outstanding Engineer** Award (2004). He is a Distinguished Toastmaster (DTM) who led District 13 of Toastmasters International (TI) as its Governor to be the 10th-ranking District in the world in 2007–2008. He has been serving as a Boy Scouts of America Leader for almost a decade.

Mey Ling Sen was born in Aruba, Dutch Caribbean. She received BSEE (high distinction, 1988) and MEE (1990) degrees from *Worcester Polytechnic Institute* (USA) and *Rice University* (USA), respectively. As an Engineering Consultant, she worked at ABB and Westinghouse/CW. She is the Co-Founder and Chief Operating Officer of Sen Engineering Solutions, Inc. She is the co-inventor of the Sen Transformer, which is used as a Specific, Measurable, Attainable, Relevant, and Time-bound (SMART) Power Flow Controller that is based on functional requirements and a cost-effective solution. Her interests are in power electronics, electrical machines, and electric power engineering.

As a member of IEEE, she has served the Pittsburgh Chapters of PES and IAS in various positions, including Chapter Chair. Both Chapters received the "Outstanding Large Chapter" awards for their activities in 2008 and 2009, respectively. She also served IEEE Pittsburgh Section as the Treasurer in 2012 and Chair of Women in Engineering in 2016 and 2018–2019. She has been serving as the Special Events Chair of the IEEE Pittsburgh Section since 2020. She received IEEE Pittsburgh Section Power & Energy Society **Outstanding Engineer** Award (2018). She is a Distinguished Toastmaster (DTM). She served as the TI's President's Distinguished Area Governor in 2007–2008.

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Foreword

This book is a product of the authors' five decades of combined experiences in the research and development of power flow control technology. The traditional power grid as we know it is changing drastically. Mega-sized wind and solar projects are being integrated into the traditional majority carbon-based power grid in order to curb the production of greenhouse gases significantly.

Power systems of today were designed based on central generating stations and transmission and distribution lines to get the energy to the loads. However, with land-based and off-shore wind plants and distributed and utility-scale solar plants being connected to the grid, the old paradigm does not work since the geographic locations of the renewable resources do not in general coincide with the traditional generating plants. There is a need for the T&D systems to be revisited and modified/upgraded for the new power flow regimes. The line impedances that were tuned or optimized to serve certain flow patterns may now hinder delivery of the renewable energy to the desired destinations. The intermittent nature of the renewable energy sources brings additional challenges to system frequency and voltage control and to adopting the needed dynamic capability and the ability to control power flows bidirectionally at the right price. This can be mitigated with impedance regulation in strategically-selected transmission corridors. Furthermore, in many localities there are no new right-of-ways (ROWs), and rebuilding is limited to existing ones. Even though rebuild could be inevitable, flow control may help in some scenarios and may be much more economical.

The key to a clean energy transition depends on the electric grid's ability to generate and distribute renewable energy through the transmission and distribution system. The intermittency of supply and bidirectional flows, coupled with the remote locations of solar and wind projects, are challenging grid planners and operators. Even before we have reached large penetration of renewables, forecasters are factoring renewable curtailment as a major strategy to balance supply and demand, which adversely impacts the economics of the projects.

The concept of a SMART Power Flow Controller, developed in this book, is based on impedance management of the transmission line, which will be essential to (1) building the capacity to integrate and expand the use of clean distributed energy resources, (2) pursuing efficient asset utilization and reducing system losses, (3) facilitating greater transfer of clean energy from generation sites to load centers, and (4) improving grid reliability and resiliency. This technology can be customized, based on the required range and speed of operation, component non-obsolescence, ease of relocation, and interoperability.

This book starts with the derivation of the fundamentals of power flow in an AC transmission line and develops various solutions that can be used to enhance power flow while reducing the losses in AC transmission lines. The book builds on the evolution of power flow controllers in AC transmission systems covering the theory, modeling, and various applications. The subject is treated from the working engineers' point of view. After reading the appropriate parts of this book, students, teachers, and practicing engineers will be able to conduct studies of power system networks to mitigate their unique power flow problems.

The book's unique contribution is that it

- provides the basic theory and the step-by-step explanation of various power flow controllers;
- offers modeling techniques that are essential to electric utilities when conducting the needed studies and analysis;
- provides computer codes in the most widely-used Electro-Magnetic Transients Program (EMTP) formats;
- describes a new class of power flow controllers, based on the transformers/Load Tap Changers (LTCs) technology, developed by the authors and named the Sen Transformer (ST).

It is important to emphasize that the ST offers the equivalent control features of two devices – Phase Angle Regulator (PAR) and Voltage Regulator (VR) – for almost the price of one. If one purchases a PAR, which offers the phase angle or active power flow control only, the ST offers the added voltage or reactive power flow control capability with perhaps a small additional cost. The low-cost power flow control technology, such as ST, is of interest to utilities because of its simplicity, compared to power electronics inverter-based Unified Power Flow Controller.

I believe that the Sens' inventions are fundamental contributions toward the advancement of low-cost electric power flow control technology. A simulation model of the ST has already been developed in PSS/E, the most widely used load flow software, and the report is given in Appendix C. As an application example exercising the PSS/E model, it was verified that the ST performed as the most suitable candidate for power flow enhancement in a segment of the Chilean network. Also, a distribution-level Chinese demonstration of a 10-kV unit of ST confirmed the anticipated performance of the ST.

The topic of power flow control is of great interest to many power engineering professionals, utility engineers, large power equipment manufacturers, university professors, and students. The specialty of the book is that it develops the modern power flow control theories from the basics and supplements the theory with relevant computer models using the most widely used simulation software – EMTP and PSS/E. This book expands upon what the authors had presented in their last book, titled *Introduction to FACTS Controllers – Theory, Modeling, and Applications*.

In summary, the subject of power flow control cannot be overstressed; it is a very important topic to the electric power industry and electric utilities, particularly in today's environment. Due to the current need for integrating renewable energy sources into the grid reliably to reduce the carbon-based generation, electric utilities are seriously considering all available technical solutions. This is a timely book that gives the reader clear instructions on how to model, design, build, and evaluate power flow controllers. It supplements nicely the very few existing books. I realize that this book is practical, hands-on, and a true guide for the practicing engineers. The book gives significant amounts of detail in modeling and presentation that will be much appreciated by researchers/engineers in the field.

Since the 1990s, I have been interacting with Dr. Kalyan Sen on Flexible Alternating Current Transmission Systems (FACTS)-related projects. As the Lead Simulation Engineer at Westinghouse, Dr. Sen developed the FACTS models, which were essential for performing the feasibility study of the Convertible Static Compensator (CSC) FACTS project before its installation at the New York Power Authority (NYPA) Marcy 345 kV substation in central NY.

I have read this book with great interest. It is a work of love, written by two spouses who spent their entire careers in developing a much-needed power flow control technology that can help utilities worldwide to plan and operate their power grids. The specialty of the Sens' book is that it is coauthored by an engineer who actually designed and commissioned a number of power electronics-based FACTS controllers at Westinghouse since their inceptions in the 1990s. Therefore, the book includes a flavor of practical relevance. This book is going to aid the transformational change that is taking place in the electric utility industry worldwide.

White Plains, New York

Bruce B. Fardanesh Ph.D.,
IEEE Life Fellow
Vice President, System Planning & Analysis
New York Power Authority

Nomenclature

β	Relative phase angle of the series-compensating voltage with respect to the sending-end voltage
δ_s	Phase angle of the voltage at the sending end of a line
δ_r	Phase angle of the voltage at the receiving end of a line
δ	Power angle (difference of phase angles of the voltages at the two ends of a line)
δ'	Modified power angle (difference of phase angles of the voltages at the two ends of a line after compensation)
δ'_l	Lowest modified power angle
δ'_h	Highest modified power angle
ε	Least error of the calculated voltage and actually-tapped voltage in the Sen Transformer
θ	Phase-locked loop (PLL) angle
θ_I	Phase angle of the line current
θ_{VX}	Phase angle of the voltage across the line reactance
$^\circ$	Degree
φ	Power factor angle
ϕ	Phase angle between the voltage across the line reactance and the voltage difference between the sending and receiving ends
ω	Angular frequency
ψ	Phase-shift angle of the modified sending-end voltage with respect to the sending-end voltage
Ω	Unit of resistance, reactance, and impedance
a_1-b_1-c_1	Series-compensating windings in the *A* phase of ST
a_2-b_2-c_2	Series-compensating windings in the *B* phase of ST
a_3-b_3-c_3	Series-compensating windings in the *C* phase of ST
A-B-C	Exciter windings of ST
A_1-B_1-C_1	Shunt-compensating windings in the *A* phase of ST
A_2-B_2-C_2	Shunt-compensating windings in the *B* phase of ST
A_3-B_3-C_3	Shunt-compensating windings in the *C* phase of ST
A	Ampere (unit of current)
AC	Alternating Current
ANSI	American National Standards Institute
apr	Instantaneous apparent power rating
APR	Apparent Power Rating

ATC	Available Transfer Capability
b	Multiplier of V_{Xn} from 0 to 1
BPS	Bulk Power System
BTB-SSSC	Back-To-Back SSSC
BTB-STATCOM	Back-To-Back STATCOM
BYPBRK	Bypass breaker
C	Capacitance
$\cos(\varphi)$	Power factor
cp	Compensating points of the Sen Transformer
CSC	Convertible Static Compensator
c_r, $c_{s'}$, c_{se}	Intercept
d	Duty cycle
DC	Direct Current
DCLS	DC Link Switch
$\mathbf{E}$	Shunt- or series-connected voltage
EHV	Extra High Voltage
ES	Electronic Switch
F	Farad (unit of capacitance)
FACTS	Flexible Alternating Current Transmission Systems
FC	Fixed Capacitor
GaN	Gallium Nitride
GHG	Green-House Gas
GPFC	Generalized Power Flow Controller
GST	Generalized Sen Transformer
GTO	Gate-Turn Off
H	Henry (unit of inductance)
HV	High Voltage
Hz	Hertz (unit of frequency)
i	Instantaneous current, such as line current (i), exciting current (i_{ex}), sending-end current (i_s), source current (i_{src}), and so on
I	Line current magnitude
$\mathbf{I}$	Line current
IBR	Inverter-Based Resource
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
$\mathbf{I_{ex}}$	Exciter current through the primary winding of the Sen Transformer
IPFC	Interline Power Flow Controller
I_n	Natural line current magnitude
IR	Impedance Regulator
$\mathbf{I_s}$	Current at the sending end of the line
$\mathbf{I_{src}}$	Source current
I_{TCR}	Current through Thyristor-Controlled Reactor
k	Number of TCSC sections
kHz	Kilo Hertz (unit of frequency)
k_R	Factor, representing the ratio of line resistance, R, when line current is I and the line resistance, R_n, when line current is I_n.

L	Inductance
LTC	Load Tap Changer
LV	Low Voltage
MC	Magnetic Circuit
m_r, $m_{s'}$, m_{se}	Slope
ms	Millisecond
MST	Multiline Sen Transformer
Mvar	Mega VAR (unit of reactive power)
$_n$	(subscript) Natural
NC	Normally-Closed
NERC	North American Electric Reliability Corporation
NO	Normally-Open
p	Three-phase instantaneous active power
P	Active power
PAR	Phase Angle Regulator
P_{linen}	Power loss in the natural or uncompensated line
P_{link}	Active power on the common link
P_r	Active power at the receiving end of the line
P_{rh}	Highest active power at the receiving end of the line
P_{rl}	Lowest active power at the receiving end of the line
P_{rn}	Natural active power at the receiving end of the line
P_s	Active power at the sending end of the line
P_{se}	Exchanged active power by a Series Unit
P_{sh}	Exchanged active power by a Shunt Unit
P_{sn}	Natural active power at the sending end of the line
P_{src}	Active power at the source
$P_{s'}$	Active power at the modified sending end of the line
PFC	Power Flow Controller
POC	Point of Connection to the utility
PST	Phase-Shifting Transformer
pu	Per unit
q	Three-phase instantaneous quadrature power
Q	Quality factor
Q	Reactive power
QB	Quadrature Booster
Q_{linen}	Reactive power absorbed by the natural or uncompensated line
Q_{link}	Reactive power on the common link
Q_r	Reactive power at the receiving end of the line
Q_{rh}	Highest reactive power at the receiving end of the line
Q_{rl}	Lowest reactive power at the receiving end of the line
Q_{rn}	Natural reactive power at the receiving end of the line
Q_s	Reactive power at the sending end of the line
Q_{se}	Exchanged reactive power by a Series Unit
Q_{sh}	Exchanged reactive power by a Shunt Unit
Q_{sn}	Natural reactive power at the sending end of the line
Q_{src}	Reactive power at the source

$Q_{s'}$	Reactive power at the modified sending end of the line
r_k	Voltage error at a possible k^{th} operating point in the Sen Transformer
R	Line resistance
R'	Resistance of a section of a line
R_{eff}	Effective line resistance
ROM	Rough-Order Magnitude
RMS	Root Mean Square
RR	Reactance Regulator
R_{se}	Series-compensating resistance
R_{sh}	Shunt-compensating resistance
s	Second
S	Apparent power
SiC	Silicon Carbide
SMART	Specific, Measurable, Attainable, Relevant, and Time-bound
SPFC	SMART Power Flow Controller
S_r	Apparent power at the receiving end of the line
S_s	Apparent power at the sending end of the line
$_{se}$	(subscript) Series-exchanged, *i.e.* c_{se}, m_{se}, P_{se}, R_{se}, X_{se}, Q_{se}, Z_{se}
S_{se}	Exchanged apparent power by a Series Unit
$_{sh}$	(subscript) Shunt-exchanged, *i.e.* P_{sh}, R_{sh}, X_{sh}, Q_{sh}, Z_{sh}
S_{sh}	Exchanged apparent power by a Shunt Unit
SSSC	Static Synchronous Series Compensator
$S_{s'}$	Apparent power at the modified sending end of the line
ST	Sen Transformer
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
SynCon	Synchronous Condenser
t	Time
TCR	Thyristor-Controlled Reactor
THD	Total Harmonic Distortion
TNA	Transients Network Analyzer
TSC	Thyristor-Switched Capacitor
TSR	Thyristor-Switched Reactor
TTC	Transmission Transfer Capability
UHV	Ultra High Voltage
UPFC	Unified Power Flow Controller
UPS	Uninterruptible Power Supply
v	Instantaneous voltage
V	Phase voltage magnitude
$\mathbf{V}$	Phasor voltage
V	Volt (unit of voltage)
va	volt-ampere (unit of instantaneous apparent power)
VA	Volt-Ampere (unit of apparent power)
VAR	Volt-Ampere Reactive (unit of reactive power)
VR	Voltage Regulator
VRT	Voltage-Regulating Transformer

VSC	Voltage-Sourced Converter
$\mathbf{V_d}$	Voltage across the compensating resistance
$\mathbf{V_{dq}}$	Voltage across the compensating impedance
$\mathbf{V_q}$	Voltage across the compensating reactance
$\mathbf{V_r}$	Voltage at the receiving end of the line
$\mathbf{V_s}$	Voltage at the sending end of the line
$\mathbf{V_{s'}}$	Voltage at the modified sending end of the line
$\mathbf{V_{s'h}}$	Highest voltage at the modified sending end of the line
$\mathbf{V_{s'l}}$	Lowest voltage at the modified sending end of the line
$\mathbf{V_{s's}}$	Series-compensating voltage
$\mathbf{V_R}$	Voltage across the line resistance
$\mathbf{V_{Rn}}$	Natural voltage across the line resistance
$\mathbf{V_{R,X}}$	Voltage across the line impedance ($\mathbf{Z} = R + j\mathrm{X}$)
$\mathbf{V_{Rn,Xn}}$	Natural voltage across the line impedance ($\mathbf{Z} = R + j\mathrm{X}$)
$\mathbf{V_X}$	Voltage across the line reactance
$\mathbf{V_{Xn}}$	Natural voltage across the line reactance
W	Watt (unit of active power)
WECC	Western Electricity Coordinating Council
X	Line reactance (total)
X'_C	Capacitive reactance of a section of a line
X_{eff}	Effective line reactance
X'_L	Inductive reactance of a section of a line
X_{se}	Series-compensating reactance
X_{sh}	Shunt-compensating reactance
Z_{se}	Series-compensating impedance
Z_{sh}	Shunt-compensating impedance

Preface

Both authors have been involved in exploring various power flow controllers since the early 1990s. Kalyan Sen developed power electronics inverter-based Flexible Alternating Current Transmission Systems (FACTS) models while working at Westinghouse where pioneering development of FACTS products took place. Note that a forced-commutated inverter with a DC link capacitor is also referred to as a Voltage-Sourced Converter (VSC). Being an active contributor through patents, publications, design, and commissioning of much-advertised FACTS controllers since its inception in the 1990s, Kalyan has a first-hand knowledge of specific applications where the inverter-based controllers are the desirable solutions and where these solutions are not suitable at all. He has written an award-winning technical committee paper on the modeling of Unified Power Flow Controller (UPFC) in the *IEEE Transactions on Power Delivery*. Mey Ling Sen explored an alternate approach to the VSC-based FACTS Controllers that is cost effective while meeting functional requirements for most utility applications. This effort led to the concept of the Sen Transformer (ST). The ST is fundamentally different from the conventional transformer, in a sense that it uses three primary windings and nine secondary windings to create a compensating voltage that modifies the line voltage to be a specific magnitude and phase angle, whereas the conventional transformer only modifies the magnitude of the line voltage. As a result, by using an ST, the active and reactive power flows in the line can be regulated independently to maximize the revenue-generating active power flow and minimize the reactive power flow while maintaining the stability of the line voltage.

Since 2002, Kalyan has traveled around the world as an IEEE Distinguished Lecturer and lectured in more than 150 places in 15 countries. When he gives a presentation on power flow controllers, his approach is to start from the basics and lead up to the advanced concept of VSC-based FACTS Controllers and 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, which resulted in the publication of *Introduction to FACTS Controllers: Theory, Modeling, and Applications* in 2009. At the inception of the FACTS development in the 1990s, the main concerns were the high installation and operating costs of the FACTS Controllers. Over the decades, the list of drawbacks has expanded to include component obsolescence, costly maintenance, lack of trained-labor, impracticability of relocation and lack of interoperability. A desired feature of a Power Flow Controller (PFC) is that it is easily relocatable to wherever it is needed the most, since the need for power flow control may change with time due to new generation, load, and so on. Interoperability is desired so that components from various suppliers can be used, resulting in a global manufacturing standard, ease of maintenance, and ultimately lower cost to consumers.

The utilities are searching for a suitable power flow controller that offers its inherent features: simplicity, operational reliability, cost-effectiveness, component non-obsolescence, high efficiency, low maintenance, ease of relocation, and interoperability to meet their immediate needs to relieve grid congestion due to overload, peak load demand, and integration of renewable energy sources into the grid. The ST combines the best features of the FACTS controllers in terms of the ability to independently control active and reactive power flows while using time-tested and reliable transformer/Load Tap Changers (LTCs) technology that are familiar to the utilities worldwide for almost a century. More on LTCs can be found in the book, titled *On-Load Tap-Changers For Power Transformers: Operation, Principles, Applications and Selection*, by A. Krämer, Maschinenfabrik Reinhausen, 2000.

Power transformers are the workhorses that make transmission and distribution of AC electric power possible. Transformers step up the generator voltage (*e.g.* 25 kV) to the transmission level (*e.g.* 345 kV) and step down to distribution level (*e.g.* 13.8 kV) and, finally, to household utilization voltage (*e.g.* 120/240 V). With the addition of an LTC under load, transformers can easily regulate voltage. Specialty transformers, such as Phase Angle Regulators (PARs), can also regulate phase angle of the line voltage. The ST can regulate both the voltage magnitude and the phase angle simultaneously; as a result, the active and reactive power flows through the line can be controlled independently as desired.

The primary goal of this book is to present the fundamentals so that readers can retain the information clearly in their minds and provide a meaningful input in the selection process of adopting a particular solution. The book describes various concepts that are applicable to electric power industries. The concepts can be applied using traditional non-power electronics-based solutions and modern power electronics-based solutions or some hybrid of traditional-modern solutions. The reason for the primary goal is that a particular solution becomes obsolete as time progresses; however, the fundamental concepts remain the same.

Early power flow controllers employed basic technologies, such as transformers, capacitors, and reactors for the compensating voltage injection into the line. Later designs used power electronics to achieve much greater flexibility and optimization through an independent control of active and reactive power flows. When the first generation of power flow controllers, based on power electronics VSCs, were built in the 1990s, the Gate-Turn-Off thyristor (GTO) was the forced-commutated semiconductor switch of choice because of its availability in high power rating (4500 V, 4000 A) and its low forward voltage that resulted in low conduction loss. Early FACTS Controllers used VSCs with GTOs, switching once-per-cycle that resulted in the lowest switching loss and the lowest overall loss of about 1% of the rating of the VSC. These VSCs used special transformers to employ harmonic-neutralized techniques and produced high-quality AC waveforms without using filters. The inherent nature of a GTO is its relatively longer turn-on and turn-off times. More commonly used modern Pulse Width Modulation (PWM) techniques are based on instantaneous turn-on and turn-off of a switch. A voltage waveform that is created with a PWM technique consists of a fundamental component of interest and harmonic components, the dominant of which is related to the ratio of the switching and the fundamental frequencies. A higher switching frequency is desirable, because the higher dominant frequency requires a reduced-sized filter. To keep the sum of turn-on and turn-off times of a GTO to be less than 1% of the switching period, it would result in only several hundred Hz of switching frequency. This would require a fairly large-sized output filter to eliminate the unwanted low-order harmonic components, generated by a force-commutated inverter.

About a decade later, the VSC of choice started to use Insulated Gate Bipolar Transistor (IGBT)-based PWM techniques. An IGBT offers shorter turn-on and turn-off times, which is less than 1% of the switching period that results in a switching frequency of several kHz. A lower switching period means a higher switching frequency and higher order harmonic components that are not of significant interest, since they do not generate significant amount of harmonic currents for two reasons; first, higher order voltage harmonic components are lower in magnitudes and second, the higher order voltage harmonic components "see" higher reactances for a given inductance. However, some filtering may still be needed, since switching frequency could not be increased to the desired level in some cases due to generation of excessive losses (3–4% of the rating of the VSC) as a function of the increased switching frequency. Another decade later, the topology of choice has become multilevel VSCs that do not need any harmonic filtering. While the topologies of VSCs are changing, so are the semiconductor switching devices. The upcoming switches are based on silicon carbide (SiC) and gallium nitride (GaN) for desirable reasons, such as high-speed operation, which results in lower turn-on and turn-off times, thus lower switching loss, high-temperature operation, lower cooling requirement, and smaller circuits for the gate drive and the snubber. A higher switching frequency creates a higher Electro-Magnetic Interference (EMI), which requires the use of an additional EMI filter. The fact is that with various advances in the power electronics technology and semiconductor switches, the FACTS controllers become obsolete in a relatively few years and as a result, a one-to-one component replacement becomes impossible in 10–15 years. In the utility world where 45–50 years of equipment life is the norm, this means the entire power electronics inverter-based FACTS installation may need to be replaced several times in those 45- to 50-year period. In addition, simple maintenance requires highly skilled personnel that are not readily available. The global standard and interoperability do not exist due to a limited number of manufacturers. This is a highly expensive proposition perhaps two orders of magnitude more than a long-lived and easily maintained transformer/LTCs-based technology, such as ST.

Today's power grid has evolved into integration of inverter-based, renewable-sourced, electricity generation from solar and wind farms, which are intermittent in nature. Therefore, traditional steady-state power flow controllers, such as series-connected reactor/capacitor concepts, need to be updated with an improved dynamic response. Additionally, increasing installation of roof-top solar and its integration into a low-voltage distribution network has altered the traditional voltage profile in the distribution network and increased the need for a bidirectional power flow controller when the renewable generation is not available. Therefore, all available solutions need to be considered for future needs, which has led to the concept of SMART Controllers.

A considerable amount of effort has been put into modeling various controllers. Modeling is the only approach, before any hardware construction, for the verification of the performance of any concept. The book includes models of many controllers, developed using a freely available Electro-Magnetic Transients Program (EMTP) software package.

The book is divided into six chapters and three appendices. Chapter 1 presents the origin of power flow controllers and guides the reader to the selection process of a SMART Power Flow Controller (SPFC).

Chapter 2 is for anyone who would like to become familiar with the subject. It discusses various topics of the book in simple electrical engineering terms and corroborates the theory with relevant mathematics. The characteristic equations of various power flow controllers, including their equivalent compensating impedances, are developed. Using these equations, a set of example problems is given, which gives a quick back-of-the-envelope calculation results without much effort. A figure of merit, called *Sen Index*, is defined for all the Power Flow Controllers (PFCs).

Chapter 3 presents the fundamentals of modeling in EMTP and explains the basic differences of modeling various PFCs, such as the Voltage-Regulating Transformer (VRT), Phase Angle Regulator (PAR), Unified Power Flow Controller (UPFC), and Sen Transformer (ST). Following the Rough-Order Magnitude (ROM) calculations performed in Chapter 2, using simple equations to characterize a power flow solution, the ROM results may need to be refined by employing the modeling techniques developed in Chapter 3. An example simulation of a series-compensating voltage is shown to emulate a VRT, a PAR, and an Impedance Regulator (IR).

Chapter 4 presents the transformer-based PFCs and gives some baseline examples for comparison with other PFCs in the following chapters. It is shown how a VRT and a PAR may be modeled by using a series-compensating voltage.

Chapter 5 presents some early PFCs that use mechanical switches and set some baselines for comparison in the following chapters. It is shown how to model a virtual impedance that is equivalent to shunt-connected and/or series-connected inductive and/or capacitive compensators.

Chapter 6 presents the evolution of an ST and its wide variety of applications. The most up-to-date advancements in ST are described in this chapter. This includes various forms of two-core designs. Also included is a new factory-test method under full power.

Appendix A describes the operation of various items, such as (1) three-phase balanced and unbalanced voltage, current, and power; (2) symmetrical components; (3) d-q transformation; and (4) Fourier analysis. The reader will find it useful to see the industry techniques and the relevance of the theory and applications.

Appendix B presents the power flow control equations in a lossy line and compares the derived results from those in Chapter 2 for lossless lines. Simpler versions of these equations are derived in Chapter 2, considering the line resistance (R) is zero. These examples will be used as future references for those involved with PFCs. For the readers to recognize the importance of the equations and example solutions presented in Chapter 2, a list of all the "Examples" is placed at the end of Appendix B. Using the information received from Supervisory Control And Data Acquisition (SCADA) about the sending- and receiving-end voltages (V_s and V_r) and active and reactive power flows (P_r and Q_r), other power flow variables, such as the power angle (δ), can be calculated for a known line impedance ($\mathbf{Z} = R + jX$).

Appendix C presents a load flow study of the Chilean network, integrated with Sen Transformer, performed by Siemens PTI and sponsored by New York Power Authority.

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