UNIVERSITI PUTRA MALAYSIA

DESIGN AND MODELING OF POWER TRANSISTOR-ASSISTED SEN TRANSFORMERS FOR TRANSMISSION GRID POWER FLOW CONTROL

SALAH ELDEEN GASIM MOHAMED HASSAN

FK 2017 110

DESIGN AND MODELING OF POWER TRANSISTOR-ASSISTED SEN TRANSFORMERS FOR TRANSMISSION GRID POWER FLOW CONTROL

By

SALAH ELDEEN GASIM MOHAMED HASSAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

July 2017

COPYRIGHT

DEDICATION

To the sole of my father, to my mother, wife, and brothers and sisters

with sincere and exceptional love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DESIGN AND MODELING OF POWER TRANSISTOR-ASSISTED SEN TRANSFORMERS FOR TRANSMISSION GRID POWER FLOW CONTROL

By

SALAH ELDEEN GASIM MOHAMED HASSAN

July 2017

Chair: Associate Professor Jasronita Jasni, PhD
Faculty: Engineering

Many arising factors endanger the secure and stable operation of transmission grids. Those are deregulation that opens transmission grid, increasing dynamics in consequence of wide integration of variable renewable energy sources, unwillingness to install new transmission lines, electric power demand increase, resulting stress that causes frequent components outage, uneven distribution of power in transmission lines, and resulting low utilization of existing transmission grid infrastructure. In consequence, the need to widely use transmission grid power flow controllers is escalating. However, these power flow controllers need to be reasonably costing as well as technically competent. Three main families of existing power flow controllers are conventional power flow controllers, flexible AC transmission systems controllers, and hybrid power flow controllers, which all have their pros and cons. Conventional power flow controllers are cost-effective, however, have technical shortcomings. Flexible AC transmission systems controllers are technically competent but their cost is high. Hybrid power flow controllers combine some advantages of the other two families, however, have their own limitations, and their cost is still high. Combination of most technical advantages of existing power flow controllers in a single power flow controller at a reasonable cost is promising. Based on a comprehensive review, a family of power transistor-assisted Sen Transformers that bridges the gap between unified power flow controller and Sen Transformer is proposed. Power transistor-assisted Sen Transformers are designed and their comprehensive Simulink model is developed and tested in *MATLAB/SIMULINK*. Ratings of components of a power transistor-assisted Sen Transformer are determined and its cost is analyzed and compared to that of a similar unified power flow controller. Operation principle of power transistor-assisted Sen Transformers, operational characteristics, and control strategies are revealed. Also, a simplified Simulink model and a comprehensive Newton-Raphson model of power transistor-assisted Sen Transformers are developed and validated. Performance of power transistor-assisted Sen Transformers for enhancement of optimal power flow and also for maintaining grid security is assessed and compared to that of Sen Transformer and unified power flow controller.

Methods used include simulation using *MATLAB/SIMULINK*, analytical Newton-Raphson based load flow analysis, optimal power flow, and simple power flow equations, besides voltage vector analysis. Among the significant findings, operational characteristics of power transistor-assisted Sen Transformers are found closely comparable to those of the unified power flow controller. Power transistor-assisted Sen Transformers operate continuously and provide repeatable control action, error-free, and ensure precise control action. They have non-limited operating points within their control area and ensures increased flexibility, improved response-rate that enables mitigating transient stability problems, extended control range, and far lower cost as compared to an analogous unified power flow controller. As compared to an analogous conventional Sen Transformer, performance of power transistor-assisted Sen Transformer in enhancement of optimal power flow is found to be techno-economically feasible. Also, as compared to an analogous unified power flow controller, power transistor-assisted Sen Transformer is able to maintain grid security and found closely similar with a far lower installation cost. In conclusion, power transistor-assisted Sen Transformers are timely proposed competent and cost-effective power flow controllers those provide tremendous technical and economic benefits to the current days' and the future's smart grids.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

REKA BENTUK DAN PERMODELAN KUASA-TRANSISTOR DIBANTU ALATUBAH SEN UNTUK KAWALAN PENGHANTARAN ALIRAN KUASA GRID

Oleh

SALAH ELDEEN GASIM MOHAMED HASSAN

Julai 2017

Pengerusi: Profesor Madya Jasronita Jasni, PhD
Fakulti: Kejuruteraan

Terdapat pelbagai faktor yang timbul memberi ancaman khususnya pada operasi penghantaran grid yang selamat dan stabil. Antara faktor yang membahayakan operasi penghantaran grid termasuklah penyahkawalseliaan yang membuka penyaluran grid, peningkatan dinamik disebabkan oleh integrasi pelbagai sumber tenaga yang boleh diperbaharui yang meluas, keengganan untuk memasang talian penghantaran baru, permintaan kuasa elektrik yang meningkat, dan pengagihan talian kuasa yang tidak sekata, tekanan yang terhasil akibat komponen yang kerap terganggu meskipun penggunaan infrastruktur penghantaran grid yang kurang. Kesannya, keperluan penggunaan penghantaran aliran kuasa grid yang luas semakin meningkat. Namun begitu, untuk membolehkan penggunaan pengawal aliran kuasa yang luas, ianya memerlukan kos yang berpatutan dan cekap dari segi teknikal. Terdapat tiga kelompok utama pengawal aliran kuasa yang sedia ada iaitu pengawal aliran kuasa konvensional, pengawal sistem penghantaran arus ulang alik fleksibel, dan pengawal aliran kuasa hybrid, yang mempunyai kebaikan dan keburukan masing-masing. Pengawal aliran kuasa konvensional mempunyai kos yang efektif, walaubagaimanapun, ia mempunyai kelemahan dari segi teknikal. Pengawal sistem penghantaran arus ulang alik yang fleksibel pula cekap dari segi teknikal, namun ia memerlukan kos yang tinggi. Pengawal aliran kuasa hybrid menggabungkan beberapa kelebihan dari dua kelompok yang lain, namun begitu, pengawal aliran kuasa hybrid ini mempunyai had dan kos ia tetap tinggi. Gabungan pada kebanyakan kelebihan teknikal pengawal aliran kuasa yang sedia ada dalam pengawal aliran kuasa tunggal pada kos yang berpatutan adalah menarik. Berdasarkan pada keseluruhan kajian, kelompok transistor kuasa dibantu pengubah Sen menggabungkan jurang antara pengawal aliran kuasa bersatu dan pengubah Sen dicadangkan. Pengubah sen dibantu transistor kuasa direka dan Model *SIMULINK* komprehensif dibina dan diuji menggunakan *MATLAB/SIMULINK*. Penilaian untuk setiap komponen ditentukan dan kos pengubah sen dibantu transistor kuasa dianalisis

dan dibandingkan dengan analogi pengawal aliran kuasa bersatu. Prinsip operasi pengubah sen dibantu transistor kuasa, ciri-ciri operasi, strategi kawalan turut didedahkan. Selain itu, Model *SIMULINK* yang dipermudahkan dan Model Newton-Raphson Komprehensif daripada pengubah sen dibantu transistor kuasa turut dibina dan disahkan. Prestasi pengubah sen dibantu transistor kuasa dalam merealisasikan aliran kuasa optimum dan mengekalkan keselamatan grid telah dinilai dan dibandingkan dengan pengubah sen konvensional dan pengawal aliran kuasa bersatu. Kaedah yang digunakan juga termasuklah simulasi menggunakan *MATLAB/SIMULINK*, analisis Newton-Raphson berdasarkan aliran beban, aliran kuasa optimum dan penggunaan persamaan aliran kuasa yang mudah selain daripada analisis vektor voltan. Antara penemuan yang penting, ciri-ciri operasi pengubah sen dibantu transistor kuasa ditemui setanding dengan pengawal aliran kuasa bersatu. Pengubah sen dibantu transistor kuasa beroperasi secara berterusan dan menyediakan kawalan aksi yang berulang-ulang, tiada ralat dan memastikan tindakan kawalan yang tepat. Ia mempunyai titik operasi yang tidak terhad dalam kawasan kawalan serta memastikan peningkatan fleksibiliti, kadar tindakbalas yang bertambah baik yang membolehkan pengurangan masalah kestabilan sementara, pelbagai kawalan lanjutan dan kos yang jauh lebih rendah berbanding dengan analogi pengawal aliran kuasa bersatu. Jika dibandingkan dengan pengubah sen konvensional, pelaksanaan pengubah sen dibantu transistor kuasa dalam merealisasikan aliran kuasa optimum didapati tekno-ekonomi mampu dilaksanakan, dan jika di bandingkan dengan analogi pengawal aliran kuasa bersatu, pengubah sen dibantu transistor kuasa mampu mengekalkan grid keselamatan dan didapati hamper sama dengan kos pemasangan yang jauh lebih rendah. Kesimpulannya, pengubah sen dibantu transistor kuasa ini dicadangkan pada masa yang tepat dan kos efektif pengawal aliran kuasa yang menyediakan banyak kelebihan dari segi teknikal dan ekonomi pada penghantaran pintar pada masa kini dan akan datang.

ACKNOWLEDGEMENTS

Praise and thanks to the Almighty Allah for giving me the opportunity, determination, strength, ability, and help to complete this work. Without His blessings, this achievement would not be possible. I am extremely thankful to my wonderful supervisor Assoc. Prof. Dr. Jasronita Jasni. It is difficult to find suitable words to express my deepest gratitude for the great efforts, and continuous help and support all through the years with her knowledge, guidance and time. I am greatly thankful to members of my supervisory committee, Assoc. Prof. Dr. Mohd Amran Mohd Radzi, and Assoc. Prof. Dr. Hashim Hizam for their continuous help, efforts and support all through the years.

I would also like to acknowledge all staff members of the Centre for Electromagnetic and Lightning Protection Research (CELP), the Centre for Advanced Power Engineering Research (CAPER) and the Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia. Special thanks are due to all friends, Malaysian, international and Sudanese for their help, fine co-operation and moral support during the hard times along the journey of the PhD. I would also like to acknowledge Sudan University of Science and Technology for providing the opportunity to pursue this candidature, and for granting the study leave and scholarship.

I would also like to acknowledge my kind hearted and beloved mother Aisha Badry Hassan Awaad, kind hearted and beloved wife Rania Awad Ramadan Mohamed, and generous family, whose continuous prayers for me have resulted in this success.

I certify that a Thesis Examination Committee has met on 27 July 2017 to conduct the final examination of Salah Eldeen Gasim Mohamed Hassan on his thesis entitled "Design and Modeling of Power Transistor-Assisted Sen Transformers for Transmission Grid Power Flow Control" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Roslina binti Mohd Sidek, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Wan Fatinhamamah Wan Ahmad, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Azah Mohamed, PhD
Professor
Universiti Kebangsaan Malaysia
Malaysia
(External Examiner)

Akhtar Kalam, PhD
Professor
Australia Victoria University
Australia
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 September 2017

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Jasronita Jasni, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Amran Mohd Radzi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hashim Hizam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institution;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ______________________________ Date: ______________________________

Name and Matric No: Salah Eldeen Gasim Mohamed Hassan, GS34849

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ____________________
Name of Chairman of Supervisory Committee: Associate Professor Dr. Jasronita Jasni

Signature: ____________________
Name of Member of Supervisory Committee: Associate Professor Dr. Mohd Amran Mohd Radzi

Signature: ____________________
Name of Member of Supervisory Committee: Associate Professor Dr. Hashim Hizam

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Alternative Current
ACOPF	Alternative Current Optimal Power Flow
ASW	Active Smart Wires
ATC	Available Transfer Capability
AVR	Automatic Voltage Regulator
BES	Battery-based Energy Storage
BEST	Battery-based Energy Storage Transportation
BJT	Bipolar Junction Transistor
BTB	Back-To-Back
CB	Circuit Breaker
CD-PAR	Compact Dynamic Phase Angle Regulator
CM	Congestion Management
CMI	Cascade Multilevel Inverter
CNRM	Comprehensive Newton-Raphson Model
CNT	Controllable Network Transformer
CPFC	Conventional Power Flow Controller
CSM	Comprehensive Simulink Model
D	Duty Cycle
DC	Direct Current
DCOPF	Direct Current Optimal Power Flow
D-FACTS	Distributed Flexible AC Transmission Systems
DFC	Dynamic Flow Controller
DG	Distributed Generation
DPFC	Distributed Power Flow Controller
DR	Demand Response
DSSC	Distributed Static Series Compensator
DSI	Distributed Series Impedance
DVQS	Dual Virtual Quadrature Source
EGAT	Electricity Generating Authority of Thailand
ES	Energy Storage
ESC	Energy Storage Component
EST	Energy Storage Technology
EV	Electric Vehicle

FACTS	Flexible AC Transmission Systems
FC-TCR	Fixed Capacitor Thyristor Controlled Reactor
FR-BTB-PR	Fractionally Rated Back-To-Back Power Router
FRC	Fractionally Rated Converter
GIPFC	Generalized Interline Power Flow Controller
GR	Generation Rescheduling
GTO	Gate Turn-Off Thyristor
GUPFC	Generalized Unified Power Flow Controller
HE-UPFC	Hybrid Electromagnetic Unified Power Flow Controller
HFC	Hybrid Flow Controller
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HPFC	Hybrid Power Plow Controller
HPS	Hybrid Phase Shifter
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IOOC	Integral On-Off Control
IPFC	Interline Power Flow Controller
ISO	Independent System Operator
IST	Improved Sen Transformer
LA-ST	Limited Angle Sen Transformer
LA-TAST	Limited Angle Power Transistor-Assisted Sen Transformer
LF	Load Flow
LS	Load Shedding
MC	Matrix Converter
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
MSC	Mechanically Switched Capacitor
MSR	Mechanically Switched Reactor
OGR	Optimal Generation Rescheduling
OLTC	On-Load Tap-Changing
OPF	Optimal Power Flow
OTS	Optimal Transmission Lines Switching
OUPFC	Optimal Unified Power Flow Controller
PAC	Phase Angle Control
PEs	Power Electronics

PFC	Power Flow controller
PI	Performance Index
PST	Phase Shifting Transformer
PWM	Pulse Width Modulation
RDTR	Real-time Dynamic Thermal Rating
RMS	Root Mean Square
RM	Runkle Machine
RPST	Rotary Phase Shifting Transformer
RPFC	Rotary Power Flow Controller
RSW	Reporting Smart Wires
RT	Rotary Transformer
SCR	Silicon Controlled Rectifier
SiC	Silicon Carbide
SPS	Static Phase Shifter
SR	Saturable Reactor
SSM	Simplified Simulink Model
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
ST	Sen Transformer
SVC	Static Var Compensator
SW	Smart Wire
TACC	Thin AC Converter
TAST	Power Transistor-Assisted Sen Transformer
TCPS	Thyristor Controlled Phase Shifter
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
THD	Total Harmonic Distortion
TLOA	Transmission Lines Overload Alleviation
TNB	Tenaga Nasional Berhad
TRIAC	Triode for AC
TS	Transmission Lines Switching
TSC-TCR	Thyristor Switched Capacitor Thyristor Controlled Reactor
TSR	Thyristor Switched Capacitor
TSS	Two Separate Shafts
TSSC	Thyristor Switched Series Capacitor

TSSR	Thyristor Switched Series Reactor
TST	Transistorized Sen Transformer
TUPFC	Transformer-less Unified Power Flow Controller
UPFC	Unified Power Flow Controller
VFT	Variable Frequency Transformer
VRES	Variable Renewable Energy Source
VRT	Voltage Regulating Transformer
VSI	Voltage-Source Inverter
V2G	Vehicle To Grid

LIST OF SYMBOLS

a_o	DC component (V) or (A)
a_k and b_k	Fourier coefficients
B	Shunt susceptance of transmission line (mho), which is the imaginary part of the shunt admittance *Y*
B_{kk}	Self susceptance at bus *k* (mho)
b_{km}	Series susceptance of transmission line (mho) between buses *k* and *m*, which is the imaginary part of the series admittance Y_{km}. It includes that of the PFC if connected
c_1^k	Sensitivity of *PI* with respect to V_T
c_2^k	Sensitivity of *PI* with respect to $\emptyset_T$
D	Duty cycle
f	Frequency (Hz)
G_{kk}	Self-conductance at bus *k* (mho)
g_{km}	Series conductance of transmission line (mho) between buses *k* and *m*, which is the real part of the series admittance Y_{km}. It includes that of the PFC if connected
I	Current in a transmission line (A)
I_r	Current at the receiving end of a transmission line (A)
I_k'	Current at the effective sending end k' of a transmission line (A)
I_T	Active component of the exciter current of the TAST (A)
I_q	Reactive component of the exciter current of the TAST (A)
Im	Imaginary part of a complex quantity
J	Imaginary unit which is the root of *-1*
k	Harmonics order
m	Transmission line number
N_l	Number of transmission lines in a grid
N_b	Number of buses in the transmission grid
n	Bus number
n	Real positive integer
P_s	Active power at the sending end of a transmission line (W)
P_r	Active power at the receiving end of a transmission line (W)
P_n	Active power injected at bus *n* (W)
P_{js}	Addition in the injected active power at bus *j* as a consequence of the presence of the PFC (W)

P_{km}	Active power flow from bus *k* to bus *m* (W)
P_{lm}	Active power flow in line *m* (W)
P_i^1	Active power flow in line *i* at terminal bus *1* (W)
P_{lm}^{max}	Maximum allowed active power flow in line *m* (W)
$P_{se(TAST)}$	Active power of the series part of TAST (W)
$P_{sh(TAST)}$	Active power of the shunt part of TAST (W)
P_{exch}	Active power exchange between line and TAST (W)
Q_s	Reactive power at the sending end of a transmission line (VAR)
Q_r	Reactive power at the receiving end of a transmission line (VAR)
Q_i^1	Reactive power flow in line *i* at terminal bus *1* (VAR)
Q_{exch}	Reactive power exchange between line and TAST (VAR)
Q_{km}	Reactive power that flow from bus *k* to bus *m* (VAR)
$Q_{se(TAST)}$	Reactive power of the series part of TAST (VAR)
R_i	Resistance of transmission line *i* (Ω)
Re	Real part of a complex quantity
r_{km}	Series resistance (Ω) of transmission line between buses *k* and *m*, which is the real part of the series impedance Z_{km}, it includes that of the PFC if connected
S_{km}	Apparent power that flow from bus *k* to bus *m* (VA)
$[S]$	Matrix that relates lines flow with the power injections at the buses
S_{mn}	mn^{th} element of Matrix $[S]$
s	Slack or reference bus
T	Period of a signal (s)
t	Time (s)
t_{ON}	On time (s)
t_{OFF}	Off time (s)
V_k	Voltage at bus *k* (V)
V_p	Peak voltage (V)
V_m	Voltage at bus *m*(V)
V_S	Voltage at the sending end of a transmission line (V)
V_S'	Effective sending end voltage of a transmission line (V)
V_k'	Effective voltage at bus k' (V)
V_{ST}	The series injection voltage that ST provides (V)
V_{TST}	The series injection voltage that TST provides (V)

V_{TAST}, V_T	The series injection voltage that TASTs provide (V)
V_{cR}	Magnitude of the series injection voltage of PFC (V)
$V_{T(\min)}$	Minimum series injection voltage that TASTs provide (V)
$V_{T(max)}$	Maximum series injection voltage that TASTs provide (V)
V_d	Direct axis component of the series injection voltage (V)
V_q	Quadrature axis component of the series injection voltage (V)
$v_{TST(in)}$	Input voltage of the TST (V)
$v_{TST(out)}$	Output voltage of the TST (V)
X, X_l	Series reactance of transmission line (Ω)
X_i	Reactance of transmission line *i* (Ω)
X_k	A control parameter of the PFC
X_{se}	Series reactance of the PFC (Ω)
x_{km}	Series reactance (Ω) of transmission line between buses *k* and *m*, which is the imaginary part of the series impedance Z_{km}, it includes that of the PFC if connected
Y_{km}	Series admittance of transmission line (mho) between buses *k* and *m*, It includes that of the PFC if connected
Y_{bus}	Admittance matrix of the system
Z_i	Impedance of transmission line *i* (Ω)
δ	Transmission angle (°)
δ_s	Phase angle of the voltage at the sending bus *s* (°)
δ_r	Phase angle of the voltage at the receiving bus *r* (°)
δ_s'	Phase angle of the voltage of the effective sending end (V)
δ_{cR}	Phase angle of the series injection voltage of PFC (°)
$\frac{\partial P_k}{\partial \theta_k}$	Jacobian matrix element, which is the first derivative of the active power at bus *k* to phase angle of voltage at bus *k*
ΔP_k	Active power mismatch at bus *k* (W)
ΔQ_k	Reactive power mismatch at bus *k* (VAR)
$\Delta \theta_k$	Phase angle mismatch at bus *k* (°)
ΔV_k	Voltage magnitude mismatch at bus *k* (V)
ΔP_{bb}	Active power mismatch of the shunt and series of the TAST (W)
θ_i	Phase angle of the impedance of transmission line *i* (°)
θ_k	Phase angle of voltage at bus *k* (°)
θ_m	Phase angle of voltage at bus *m* (°)
θ_{km}	Angle of the series admittance (°) of transmission line between

	buses *k* and *m*
$\emptyset_{(ST)}$	Angle of the series injection voltage of the ST (°)
$\emptyset_{(TST)}$	Angle of the series injection voltage of the TST (°)
$\emptyset_{(TAST)}$, $\emptyset_T$	Angle of the series injection voltage of the TASTs (°)
$\emptyset_{T(\min)}$	Minimum angle of the voltage of the TASTs (°)
$\emptyset_{T(max)}$	Maximum angle of the voltage of the TASTs (°)
ω	Angular power frequency (rad/sec)
ω_s	Angular switching frequency (rad/sec)
ω_m	Real positive weighting coefficient reflects importance of line m

LIST OF SI UNITS

Quantity	SI Unit	SI Unit Name
Voltage	V	Volt
Current	A	Ampere
Resistance	Ω	Ohm
Inductance	H	Hennery
Capacitance	F	Farad
Frequency	Hz	Hertz
Angular Frequency	rad/s	Rad per second
Phase angle	^{o}	Degree
Time	s	Second
Length	km	Kilometer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Many factors adversely affect transmission grid operation and endanger power system security and stability. Among these factors is deregulation of the electricity sector, heavy penetration of Variable Renewable Energy Sources (VRESs), increase of electricity demand, and unwillingness to install new transmission lines. Deregulation of the electricity sector makes the grid open access and gives rise to many difficulties in its operation and control [1]. Heavy penetration of VRESs, especially wind and solar is becoming more and more widespread [2, 3]. These VRESs possess an intermittent nature that accordingly increases grid dynamics, and are non-dispatch-able energy sources [4]. The steady increase in the demand for electrical energy stresses the operation [5]. It consequently increases the chance of components outage that may endanger the operation security [6, 7]. On the other hand, while some transmission lines are congested, some others are lightly loaded [8]. In most cases, utilization of the existing grid infrastructure is low [5, 9, 10]. Concurrently, transmission of more bulk active power at reasonable costs has become more essential. Suitable means for corrective actions that facilitate successful operation of the transmission grids, secure, and stabilize power system operation are crucial. Installation of new lines can relieve the stress. However, its growth rate is slow and the installation is limited by many factors such as high costs, public policies and right of way [5, 11]. Accordingly, there is a relatively small investment in the transmission networks [12, 13]. Also, installation of new lines may not add the required degree of controllability, flexibility, selectivity, precision, and fast control. In such circumstances, a smarter and more dynamically controllable grid is of paramount importance [14]. Greater operating flexibility and controllability are significant as they enable meeting the needs of modern power systems [15]. To this end, implementation of transmission grid Power Flow Controllers (PFCs) and their wide use is imperative as they provide economic and effective solutions [5, 16]. The continuous control enables smooth moving from a steady-state operating condition to another and prevents systems collapse [7]. Besides, the PFCs can realize a self-healing grid that can flexibly, precisely, and quickly respond to the varying operating conditions, and enable harvesting more power from the VRESs. Also, they can augment the power transfer capability and delay or even eliminate the need to install new lines and to ensure the system is able to operate optimally, securely and stably. Nonetheless, both technically and economically attractive PFCs should be used.

Existing transmission grid PFCs can be divided mainly into Conventional PFCs (CPFCs), Flexible AC Transmission Systems (FACTS) controllers, and Hybrid PFCs (HPFCs). CPFCs include mechanically switched capacitors and reactors, transformer and On-Load Tap-Changing (OLTC)-based PFCs such as the Voltage Regulating Transformer (VRT), Phase Shifting Transformer (PST), and recently, Sen

Transformer (ST) and Limited Angle STs (LA-STs) [17, 18]. They also include rotational PFCs, which are the Variable Frequency Transformer (VFT) and Rotary PFC (RPFC). Most dominant FACTS controllers are the Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Compensator (STATCOM), Static Series Synchronous Compensator (SSSC), Thyristor Controlled Phase Shifter (TCPS), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC) [19]. Finally, HPFCs are the Improved ST (IST), Hybrid Phase Shifter (HPS), Hybrid Flow Controller (HFC), Controllable Network Transformer (CNT), Fractionally Rated Back-to-Back converter-based Power Router (FR-BTB-PR), and Compact Dynamic Phase Angle Regulator (CD-PAR).

Advantages of the CPFCs include providing compensation voltage with system frequency without any harmonics, high efficiency, and for most of them, simple construction and simple control [17, 20, 21]. They are also based on technologically proven components and are generally less expensive. Challenges of the CPFCs include their step-wise operation [18], limited operating points and thus, less flexibility, control-error for the transformer and OLTC-based PFCs [20, 22, 23]. They also include the complexity, and rating limitations for the rotational PFCs, as well as the relatively slow response for the rotational PFCs, and slower response in the range of 2 seconds to switch between adjacent taps for OLTC-based CPFCs [18, 24]. It is often not possible to maintain the reliability by conventional mechanical means alone [7].

Advantages of FACTS controllers include their continuous operation mode, high flexibility, precise and tight transmission control action, and fast acting capability [7, 18]. Challenges of FACTS controllers include their high installation costs [21] and thus limited use [25-27], and relatively high operational losses [17, 21]. They also include production of harmonics that necessitate more costly converter topologies or extra components for neutralization, complex construction [28] and complex and expensive control [20].

Advantages of HPFCs include integration of fractionally-rated components that are low-costing and add advantageous characteristics such as the continuous operation mode, high flexibility, precise and error-free control action, and fast response [22]. Challenges of HPFCs differ for the different types with different components and operation principles. They include level of complexity of construction and control, the cost which, is generally less compared to that of the FACTS, but, is still high [29] and the low order harmonics that some of them produce [30, 31]. They also include the power flow control range that they cover as some of them only control active power [32]; some are optimized for active power flow control [30] and some for reactive power flow control [31]. Also, some operate in step-wise mode [33], and some combine energy storage components [23, 34] that may reduce their reliability.

1.2 Problem Statement

In present and future circumestances of power transmission grids, there is an increasing flexibility and controllability requirement [35, 36] owing to existence of many challenging factors [37]. Also, extensive use of FACTS controllers is the main goal ever since their first development [19, 38] as they present key remedies to the power grids arising problems. However, PFCs that are technically competent to realize the transmission grid control goals, and economically effective to enable the wide use, are essential. Nonthless, installation and operating costs of the FACTS controllers, in particular the Unified Power Flow Controller (UPFC), are high [19, 21, 39, 40]. As a result, there are only three practically installed UPFCs currently [25-27]. Conversely, the comparable conventional Sen Transformer (ST) is relatively cheap [17, 18, 41-43], but, has some technical drawbacks. The step-wise operation, limited operating points, less flexibility, control-error [23], and the relatively slow response of the conventional ST cannot always ensure the exact precision, and desired degree of flexibility and response-rate [15]. While there is an increasing flexibility and controllability requirement in transmission grid operation and control, the high cost of the UPFC negates its wide use, and the technical drawbacks of the ST result in limitations in degree of flexibility, controllability, and preciseness. There is technology gap between the ST and the UPFC that is beneficial to bridge. Bridging such gap enables wide use of effective PFCs to meet the increasing flexibility and controllability requirements.

1.3 Aim and Objectives of Thesis

Difficulty of maintaining secure, stable, and optimized operation of power grids is increasing [44-46]. This situation augments the needs for flexible and self healing grids. In response to that, this thesis aims to bridge the technology gap between the ST and the UPFC to contribute towards meeting the increasing needs to use PFCs in transmission grids, by proposing Power Transistor Assisted ST (TAST) and Limited Angle TASTs (LA-TASTs) as technically competent and economically attractive PFCs. The thesis also aims to techno-economically assess performance of TASTs in significant applications in different power grid test systems.

The objectives, which are set to meet these aims, are:

i. To design the TASTs, determine ratings of their components, and develop their Comprehensive *SIMULINK* Model (CSM).
ii. To demonstrate the operational characteristics and control strategies of TAST, test its action, and compare it to that of conventional ST and UPFC, and to investigate the installation costs of a TAST, and compare it to that of a similar UPFC.
iii. To develop the mathematical Comprehensive Newton-Raphson (NR) Model (CNRM) and the Simplified *SIMULINK* Model (SSM) of the TAST and compare them.

iv. To assess performance of a TAST in enhancement of the OPF and also in maintaining transmission grid security, and comparing it to similar conventional ST and/or UPFC.

1.4 Scope of Research

Scope of this research covers device level and power system level. In the device level, following a comprehensive review of existing PFCs, a set of new PFCs is proposed. It is the family of TASTs that consists of a basic ST and a fractionally rated Transistorized ST (TST). The TAST is designed and then modeled in *MATLAB/SIMULINK* including the power circuits and the IGBT′s driving circuits. The work includes determination of ratings of the components and selection of a suitable AC-AC voltage regulator, the AC-AC chopper, that fits the operation principle of the TAST, and selection of a suitable switching technique. Different control strategies of the TAST are presented. Besides, a TAST′s and equivalent ST′s and UPFC′s operating areas are compared. The work also included demonstration of the improved response rate of TAST as compared to that of conventional ST, and performing harmonics analysis. TAST′s cost analysis and comparison with that of a similar UPFC is presented. Additionally, to cover a narrower operating area at a lesser cost, the LA-TASTs are proposed, designed and modeled. In power system level that is related to steady-state power system analysis, performance of TAST is assessed and compared to that of conventional ST and/or UPFC. For that purpose, firstly, power grids including a TAST are modeled in environment of *MATLAB/SIMULINK*. Then, the mathematical CNRM of the TASTs is developed for use in the steady-state Load Flow (LF) analysis. Finally, performance of the TAST is assessed in two significant applications; enhancement of the OPF to reduce the generation cost, and enhancement of transmission grid security.

The research facilitates meeting the increasing requirement of grid controllability and flexibility [47-49] through use of competent and cost effective novel PFCs. The research rectifies the economic demerits of the UPFC and the technical drawbacks of the conventional ST. Possessing most advantages of the UPFC and conventional ST, the TASTs bridge the technology gap. The TASTs provide closely comparable characteristics to the UPFC at far lower cost and thus can be widely used. In the current circumstances of grid operation and the continuing trends, the TASTs represent timely proposed valuable tools that can aid the security and stability, and optimize operation of power systems. TASTs can help open up transmission lines′ bottlenecks to push huge amounts of active power, and better utilize the existing grid infrastructure. They can aid integration of more VRESs, and ease harnessing much more of their power. The continuous and smooth control action of the TASTs is advantageous as such characteristics provide repeatable option for power system control [50-52]. The error-free control of the TASTs ensures that it is able to provide the desired precise control action similar to that achieved by a UPFC conversely to the conventional ST [41]. The non-limited operating points of the TASTs, within their control range, provide increased flexibility to grid operations and a performance that is closely similar to that of UPFC. Nonetheless, besides the advantageous technical features, cost of the TAST is far lower compared to that of the UPFC. Moreover, the extended control range of the TAST reveals that it can operate in some cases beyond the limits of a UPFC that costs more. Also, the improved response of the TAST (in the range of milliseconds) within the operating circles of the TST enables the TAST to mitigate transient stability problems, and control the VRESs to harness more of their power [50].

i. A novel TAST is proposed for use in dynamic power flow control of transmission grids and enhancement of utilization of existing grid infrastructure. TAST proved to be versatile and closely comparable to UPFC with a far lower installation cost. It can replace UPFC for many utility applications.
ii. Novel LA-TASTs are proposed for dynamic power flow control of transmission grids and enhancement of utilization of existing grid infrastructure. A LA-TAST has less components count as compared to TAST and thus costs less. It covers a limited-angle control-area that is satisfactory for a specific purpose.
iii. An accurate model of TAST: CSM is developed for the use in the device level, and its results are validated.
iv. Two accurate models of TASTs: *SIMULINK*-based, and mathematical comprehensive Newton-Raphson based, are developed, and their results are validated. They are significant tools for steady-state analysis of power systems that incorporate a single TAST or more.

1.5 Outlines of Thesis

Chapter 1 highlights current state of power transmission grids, and existing transmission grid PFCs. It states the problem, introduces aim and objectives of the thesis, and finally presents scope of the research. Chapter 2 of this thesis displays the literature review. The challenges that face transmission grids and the mitigation measures are introduced. Among the mitigation measures, power flow control is emphasized. Benefits of power flow control are emphasized, its fundamental principle is presented, existing PFCs are compared, and based on that, a technology gap between most versatile existing PFCs is emphasized and family of proposed TASTs is introduced.

Chapter 3 of the thesis introduces methodology. Methods of simulation, analytical, and vector analysis are used. Simulation is performed using *SIMULINK* of *MATLAB*. Analytical methods include *Newton-Raphson* based LF analysis and simple power flow equations. Vector analysis is performed utilizing *Microsoft Visio*. Optimal power flow is performed using *MATPOWER*. TASTs are designed, and modeled and the models are validated. Ratings of its components are determined, and operation principle is introduced. More than a method is used in each single study for purpose of validation.

Chapter 4 presents results and discussion. The CSM of TAST is utilized to test its action in regulating voltage and power flow. Control strategies and operational characteristics of TAST are revealed and advantages are presented. TAST′s operational characteristics are compared to those of a similar ST. Also, installation cost of a TAST is analyzed and compared to that of a similar UPFC. Validity of the SSM and CNRM is demonstrated prior to their use in power system level. Finally, performance of the TASTs is assessed in two different applications, which are enhancement of the OPF and transmission grid security. In the first application, TAST is techno-economically compared to a similar conventional ST. In the second, TAST is compared to a similar UPFC bearing in mind regulating voltage of shunt bus of the UPFC.

Chapter 5 concludes the thesis. It highlights significance of the research, stresses the findings in line with the objectives, and states key contributions of the thesis. It then acknowledges the limitations, and gives recommendations for future research. Finally, list of the publications that are accompanied by the thesis is provided.

REFERENCES

[1] Y. Ni, J. Zhong, and H. Liu, "Deregulation of power systems in Asia: special consideration in developing countries," in *Power Engineering Society General Meeting, 2005. IEEE*, 2005, pp. 2876-2881.

[2] O. Edenhofer, L. Hirth, B. Knopf, M. Pahle, S. Schlömer, E. Schmid, and F. Ueckerdt, "On the economics of renewable energy sources," *Energy Economics,* vol. 40, pp. S12-S23, 2013.

[3] L. Wang and L.-Y. Chen, "Reduction of power fluctuations of a large-scale grid-connected offshore wind farm using a variable frequency transformer," *IEEE Transactions on Sustainable Energy,* vol. 2, pp. 226-234, 2011.

[4] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied Energy,* vol. 137, pp. 511-536, 2015.

[5] M. N. Nazir, S. Omran, and R. Broadwater, "Feasibility of DSR applications in transmission grid operation — control of power flow and imbalanced voltage," *Electric Power Systems Research,* vol. 131, pp. 187-194, 2016.

[6] A. Chakrabarti, *Power System Dynamics and Simulation*. Delhi: PHI Learning Pvt. Ltd., 2013.

[7] N. G. Hingorani, "Flexible AC transmission," *IEEE Spectrum,* vol. 30, pp. 40-45, 1993.

[8] A. Chakrabarti, *Power System Analysis: Operation And Control 3Rd Ed*. Delhi: PHI Learning Pvt. Ltd., 2010.

[9] G. Brunekreeft, M. Buchmann, C. Dänekas, X. Guo, C. Mayer, M. Merkel, C. Rehtanz, A. Göring, A. Herrmann, R. Kodali, and M. Stadler, "Regulatory pathways for smart grid development in China," in *Regulatory Pathways For Smart Grid Development in China*, ed: Springer, 2015, pp. 119-138.

[10] S. Ahmad, F. M. Albatsh, S. Mekhilef, and H. Mokhlis, "Fuzzy based controller for dynamic unified power flow controller to enhance power transfer capability," *Energy Conversion and Management,* vol. 79, pp. 652-665, 2014.

[11] P. Irwin, "Transmission at a crossroads," *Electrical World,* vol. 216, pp. 13-18, 2002.

[12] L. M. Abadie and J. M. Chamorro, "Valuing expansions of the electricity transmission network under uncertainty: the Binodal case," *Energies,* vol. 4, pp. 1696-1727, 2011.

[13] R. K. Deb, "Transmission investment valuations: Weighing Project Benefits," *The Electricity Journal,* vol. 17, pp. 55-67, 2004.

[14] H. Chen, A. R. Iyer, R. G. Harley, and D. Divan, "Dynamic grid power routing using controllable network transformers (CNTs) with decoupled closed-loop controller," *IEEE Transactions on Industry Applications,* vol. 51, pp. 2361-2372, 2015.

[15] M. Perez, A. Messina, and C. Fuerte-Esquivel, "Application of FACTS devices to improve steady state voltage stability," in *Power Engineering Society Summer Meeting, 2000. IEEE,* 2000, pp. 1115-1120.

[16] N. Johansson, "Control of dynamically assisted phase-shifting transformers," Royal Institute of Technology, KTH, Sweden, 2008.

[17] K. K. Sen and M. L. Sen, *Introduction to FACTS Controllers: Theory, Modeling, and Applications*. New Jersey: John Wiley & Sons, 2009.

[18] K. K. Sen and M. L. Sen, "Introducing the family of "Sen" transformers: a set of power flow controlling transformers," *IEEE Transactions on Power Delivery,* vol. 18, pp. 149-157, 2003.

[19] N. G. Hingorani, L. Gyugyi, and M. El-Hawary, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. New York: Wiley Online Library, 2000.

[20] M. O. Faruque and V. Dinavahi, "A tap-changing algorithm for the implementation of "Sen" transformer," *IEEE Transactions on Power Delivery,* vol. 22, pp. 1750-1757, 2007.

[21] K. K. Sen and M. L. Sen, "Comparison of the "Sen" transformer with the unified power flow controller," *IEEE Transactions on Power Delivery,* vol. 18, pp. 1523-1533, 2003.

[22] J. Yuan, L. Liu, W. Fei, L. Chen, B. Chen, and B. Chen, "Hybrid electromagnetic unified power flow controller: a novel flexible and effective approach to control power flow," *IEEE Transactions on Power Delivery,* 2016.

[23] J. Yuan, L. Chen, and B. Chen, "The improved Sen transformer—a new effective approach to power transmission control," in *Energy Conversion Congress and Exposition (ECCE), 2014 IEEE*, 2014, pp. 724-729.

[24] K. K. Sen and M. L. Sen, "Versatile power flow transformers for compensating power flow in a transmission line," U.S. Patents 6335613, 6384581, 6396248, and 6420856, 2002.

[25] S. Kim, J. Yoon, B. Chang, and D. Baek, "The operation experience of KEPCO UPFC," in *Electrical Machines and Systems, 2005. ICEMS 2005. Proceedings of the Eighth International Conference on*, 2005, pp. 2502-2505.

[26] B. Shperling, J. Sun, and S. Bhattacharya, "Power flow control on 345 kV lines with the 200 MVA convertible static compensator," in *Power Tech, 2005 IEEE Russia*, 2005, pp. 1-7.

[27] C. Schauder, E. Stacey, M. Lund, L. Gyugyi, L. Kovalsky, A. Keri, *et al.*, "AEP UPFC project: installation, commissioning and operation of the ±160 MVA STATCOM (phase I)," *IEEE Transactions on Power Delivery,* vol. 13, pp. 1530-1535, 1998.

[28] S. Pedakotaiah and A. Santosh, "Simulation of distributed power-flow controller (DPFC)." Research Inventy: *International Journal of Engineering and Science*. vol. 2 (1), pp. 25-32, 2013.

[29] R. P. Kandula, "*Power Router based on a Fractionally-rated Back-to-Back (FR-BTB) Converter*," PhD Thesis, Georgia Institute of Technology, Georgia, 2014.

[30] A. Prasai, R. Kandula, R. Moghe, T. Heidel, C. Schauder, and D. Divan, "Compact dynamic phase angle regulator for power flow control," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 4985-4992.

[31] D. Das, *Dynamic Control of Grid Power Flow Using Controllable Network Transformers*: Ph.D. Thesis, Georgia Institute of Technology, Georgia, 2012.

[32] B. Johnson and G. Venkataramanan, "A hybrid solid state phase shifter using PWM AC converters," *IEEE Transactions on Power Delivery,* vol. 13, pp. 1316-1321, 1998.

[33] S. A. N. Niaki, R. Iravani, and M. Noroozian, "Power-flow model and steady-state analysis of the hybrid flow controller," *IEEE Transactions on Power Delivery,* vol. 23, pp. 2330-2338, 2008.

[34] R. P. Kandula, A. Iyer, R. Moghe, J. E. Hernandez, and D. Divan, "Power router for meshed systems based on a fractionally rated back-to-back converter," *IEEE Transactions on Power Electronics,* vol. 29, pp. 5172-5180, 2014.

[35] A. Capasso, A. Cervone, M. Falvo, R. Lamedica, G. Giannuzzi, and R. Zaottini, "Bulk indices for transmission grids flexibility assessment in electricity market: A real application," *International Journal of Electrical Power & Energy Systems,* vol. 56, pp. 332-339, 2014.

[36] L. E. Jones, *Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids*. London: Academic Press, 2017.

[37] A. Gallo, J. Simões-Moreira, H. Costa, M. Santos, and E. M. dos Santos, "Energy storage in the energy transition context: A technology review," *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 800-822, 2016.

[38] N. G. Hingorani, "Power electronics in electric utilities: role of power electronics in future power systems," *Proceedings of the IEEE,* vol. 76, pp. 481-482, 1988.

[39] M. Abido, "Power system stability enhancement using FACTS controllers: A review," *The Arabian Journal for Science and Engineering,* vol. 34, pp. 153-172, 2009.

[40] M. Noroozian, L. Angquist, M. Ghandhari, and G. Andersson, "Use of UPFC for optimal power flow control," *IEEE Transactions on Power Delivery,* vol. 12, pp. 1629-1634, 1997.

[41] A. Kumar and C. Sekhar, "Comparison of Sen transformer and UPFC for congestion management in hybrid electricity markets," *International Journal of Electrical Power & Energy Systems,* vol. 47, pp. 295-304, 2013.

[42] A. Kumar and J. Kumar, "Comparison of UPFC and SEN transformer for ATC enhancement in restructured electricity markets," *International Journal of Electrical Power & Energy Systems,* vol. 41, pp. 96-104, 2012.

[43] A. Kumar and W. Gao, "Power-flow Model of “Sen” transformer for loadability enhancement and comparison with Unified power-flow controllers in hybrid electricity markets," *Electric Power Components and Systems,* vol. 37, pp. 189-209, 2009.

[44] T. R. Ayodele, A. Jimoh, J. L. Munda, and A. J. Tehile, "Challenges of grid integration of wind power on power system grid integrity: a review," *International Journal of Renewable Energy Research (IJRER),* vol. 2, pp. 618-626, 2012.

[45] M. Begovic, D. Novosel, and M. Milisavljevic, "Trends in power system protection and control," *Decision Support Systems*, vol. 30, pp. 269-278, 2001.

[46] Y. Schlumberger, C. Lebrevelec, and M. De Pasquale, "Power systems security analysis-new approaches used at EDF," in *Power Engineering Society Summer Meeting, 1999. IEEE*, 1999, pp. 147-151.

[47] H. Kondziella and T. Bruckner, "Flexibility requirements of renewable energy based electricity systems–a review of research results and methodologies," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 10-22, 2016.

[48] M. Alizadeh, M. P. Moghaddam, N. Amjady, P. Siano, and M. Sheikh-El-Eslami, "Flexibility in future power systems with high renewable penetration: A review," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1186-1193, 2016.

[49] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 785-807, 2015.

[50] U. Hager, C. Rehtanz, and N. Voropai, *Monitoring, Control and Protection of Interconnected Power Systems*. Heidelberg: Springer, 2014.

[51] E. Lerch, D. Povh, and L. Xu, "Advanced SVC control for damping power system oscillations," *IEEE Transactions on Power Systems*, vol. 6, pp. 524-535, 1991.

[52] J. J. Paserba, "How FACTS controllers-benefit AC transmission systems," in *Transmission and Distribution Conference and Exposition, 2003 IEEE PES*, 2003, pp. 949-956.

[53] H. Chandler, "Empowering variable renewables options for flexible electricity systems," *International Energy Agency, Paris, France*, 2008. https://www.iea.org/ publications/freepublications/publication/Empowering_Variable_Renewables.pdf Retrived 15/10/2016.

[54] S. Galant, E. Peirano, and L. Debarberis, "Electricity storage: a new flexibility option for future power systems," in *Advanced Technologies for Future Transmission Grids*. Heidelberg: Springer, 2013, pp. 247-284.

[55] M. Shahidehpour and M. Alomoush, *Restructured Electrical Power Systems: Operatio, Trading, and Volatility*. New York : CRC Press, 2001.

[56] S. Borenstein and J. Bushnell, "Electricity restructuring: deregulation or reregulation," *Regulation*, vol. 23, p. 46, 2000.

[57] S. Chatzivasileiadis, D. Ernst, and G. Andersson, "The global grid," *Renewable Energy*, vol. 57, pp. 372-383, 2013.

[58] O. Gore, S. Viljainen, M. Makkonen, and D. Kuleshov, "Russian electricity market reform: Deregulation or re-regulation?," *Energy Policy*, vol. 41, pp. 676-685, 2012.

[59] O. D. Rubin and B. A. Babcock, "A novel approach for modeling deregulated electricity markets," *Energy Policy*, vol. 39, pp. 2711-2721, 2011.

[60] S. Deb and A. K. Goswami, "Mitigation of congestion by generator rescheduling using particle swarm optimization," in *Power and Energy in NERIST (ICPEN), 2012 1st International Conference on*, 2012, pp. 1-6.

[61] J. Arrillaga, Y. H. Liu, and N. R. Watson, *Flexible Power Transmission: the HVDC Options*. Chippenham: John Wiley & Sons, 2007.

[62] P. Ren, "Renewables 2015 global status report," *REN21 Secretariat: Paris, France,* 2015. http://www.ren21.net/wp-content/uploads/2015/07/REN12GSR2015_Online_book_low1.pdf . Retrived 15/10/2016

[63] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 1, pp. 139-152, 2013.

[64] E. Martinot, "Renewables 2005: Global status report," *Washington, DC: Worldwatch Institute,* 2005.http://www.ren21.net/Portals/0/ documents/ activities/ gsr/RE2005_Global_Status_Report.pdf. Retrived 15/10/2016

[65] M. Zhang, D. Zhou, and P. Zhou, "A real option model for renewable energy policy evaluation with application to solar PV power generation in China," *Renewable and Sustainable Energy Reviews,* vol. 40, pp. 944-955, 2014.

[66] B. Elliston, M. Diesendorf, and I. MacGill, "Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market," *Energy Policy,* vol. 45, pp. 606-613, 2012.

[67] Z. Wang, H. Qin, and J. I. Lewis, "China's wind power industry: policy support, technological achievements, and emerging challenges," *Energy Policy,* vol. 51, pp. 80-88, 2012.

[68] B. V. Mathiesen, H. Lund, and K. Karlsson, "100% Renewable energy systems, climate mitigation and economic growth," *Applied Energy,* vol. 88, pp. 488-501, 2011.

[69] H. Lund and B. V. Mathiesen, "Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050," *Energy,* vol. 34, pp. 524-531, 2009.

[70] P. S. Georgilakis, "Technical challenges associated with the integration of wind power into power systems," *Renewable and Sustainable Energy Reviews,* vol. 12, pp. 852-863, 2008.

[71] R. Wiser, "Renewable portfolio standards in the United States-a status report with data through 2007," *Lawrence Berkeley National Laboratory,* 2008. https://emp.lbl.gov/sites/all/files/report-lbnl-154e-revised.pdf Retrived 15/10/2016.

[72] G. Papaefthymiou and K. Dragoon, "Towards 100% renewable energy systems: uncapping power system flexibility," *Energy Policy,* vol. 92, pp. 69-82, 2016.

[73] M. Huber, D. Dimkova, and T. Hamacher, "Integration of wind and solar power in Europe: Assessment of flexibility requirements," *Energy,* vol. 69, pp. 236-246, 2014

[74] P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity," *Energy Policy,* vol. 39, pp. 1817-1830, 2011.

[75] T. Hammons, A. Orths, and C. Weber, "Towards successful integration of Wind Power into European Electricity Grids: Challenges, methods and results," in

Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1-7.

[76] G. Giebel, P. Meibom, P. Pinson, and G. Kariniotakis, "Towards smart integration of wind generation," in *Nordic Wind Power Conference-NWPC'2007: Power System Integration and Electrical Systems of Wind Turbines and Wind Farms*, 2007, pp. 7 pages-ISBN 978-87-550-3640-6.

[77] A. Arabali, S. H. Hosseini, and M. Moeini-Aghtaie, "Probabilistic multi-objective transmission investment and expansion planning," *International Transactions on Electrical Energy Systems*, vol. 25, pp. 1884-1904, 2015.

[78] A. Morales-Acevedo, "Forecasting future energy demand: Electrical energy in Mexico as an example case," *Energy Procedia*, vol. 57, pp. 782-790, 2014

[79] A. El-Shazly, "Electricity demand analysis and forecasting: A panel cointegration approach," *Energy Economics*, vol. 40, pp. 251-258, 2013.

[80] M. Isaac and D. P. Van Vuuren, "Modeling global residential sector energy demand for heating and air conditioning in the context of climate change," *Energy Policy*, vol. 37, pp. 507-521, 2009.

[81] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Transactions on Power Electronics*, vol. 28, pp. 5673-5689, 2013.

[82] K. Clement-Nyns, E. Haesen, and J. Driesen, "The impact of charging plug-in hybrid electric vehicles on a residential distribution grid," *IEEE Transactions on Power Systems*, vol. 25, pp. 371-380, 2010.

[83] T. H. Oh, S. Y. Pang, and S. C. Chua, "Energy policy and alternative energy in Malaysia: issues and challenges for sustainable growth," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 1241-1252, 2010.

[84] Energy Malaysia, Volume 6, 2015 - Energy Commission. www.st.gov.my-112-energy-malaysia. Retrieved 14/8/2016.

[85] S. M. Amin and B. F. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *IEEE Power and Energy Magazine*, vol. 3, pp. 34-41, 2005

[86] Z. Bo, O. Shaojie, Z. Jianhua, S. Hui, W. Geng, and Z. Ming, "An analysis of previous blackouts in the world: Lessons for China ′s power industry," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 1151-1163, 2015.

[87] H. Pidd, "India blackouts leave 700 million without power," *The Guardian*, vol. 31, 2012.

[88] M. Vaiman, K. Bell, Y. Chen, B. Chowdhury, I. Dobson, P. Hines, *et al.*, "Risk assessment of cascading outages: Methodologies and challenges," *IEEE Transactions on Power Systems*, vol. 27, p. 631, 2012.

[89] S. N. H. V. P. Pankaj and U. Chandra, "Empowering India through integrated grid operation A case study," in *FICCI, Energy Technologies Forum*, 2008, pp. 14-21.

[90] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, *et al.*, "Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance," *IEEE Transactions on Power Systems*, vol. 20, pp. 1922-1928, 2005.

[91] J. Casazza, J. Casazza, and F. Delea, *Understanding Electric Power Systems: an Overview of the Technology and the Marketplace*. Hoboken: John Wiley & Sons, 2003.

[92] G. Zhang, Z. Li, B. Zhang, and W. A. Halang, "Understanding the cascading failures in Indian power grids with complex networks theory," *Physica A: Statistical Mechanics and its Applications*, vol. 392, pp. 3273-3280, 2013.

[93] A. Bakshi, A. Velayutham, S. Srivastava, K. Agrawal, R. Nayak, S. Soonee, *et al.*, "Report of the enquiry committee on grid disturbance in northern region on 30th July 2012 and in northern, eastern & north-eastern region on 31st July 2012," *New Delhi, India,* 2012. http://powermin.nic.in/sites/default/files/uploads/GRID_ENQ_REP_16_8_12.pdf Retrived 20/10/2016

[94] D. M. Divan, W. E. Brumsickle, R. S. Schneider, B. Kranz, R. W. Gascoigne, D. T. Bradshaw, *et al.*, "A distributed static series compensator system for realizing active power flow control on existing power lines," *IEEE Transactions on Power Delivery,* vol. 22, pp. 642-649, 2007.

[95] H. Johal and D. Divan, "Current limiting conductors: A distributed approach for increasing T&D system capacity and enhancing reliability," in *2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition*, 2005.

[96] I. Young and M. Aaron, "*Saturable Reactor for Power Flow Control in Electric Transmission Systems: Modeling and System Impact Study*," PhD Thesis, University of Tennessee, USA, 2015.

[97] S. Nuchprayoon, "Interconnections of transmission networks in Southeast Asia: A preliminary assessment for Thailand," *Natural Gas,* vol. 31, p. 27.38.

[98] H. Ren and D. Watts, "Early warning signals for critical transitions in power systems," *Electric Power Systems Research,* vol. 124, pp. 173-180, 2015.

[99] N. Palukuru, S. H. nee Dey, T. Datta, and S. Paul, "Voltage stability assessment of a power system incorporating FACTS controllers using unique network equivalent," *Ain Shams Engineering Journal,* vol. 5, pp. 103-111, 2014.

[100] A. Y. Abbas, S. E. G. M. Hassan, and Y. H. Abdelrahim, "Transmission lines overload alleviation by generation rescheduling and load shedding," *Journal of Infrastructure Systems,* vol. 22, p. A4016001, 2016.

[101] M. M. Othman and S. Busan, "A novel approach of rescheduling the critical generators for a new available transfer capability determination," *IEEE Transactions on Power Systems,* vol. 31, pp. 3-17, 2016.

[102] K. Muthulakshmi and C. Babulal, "A Novel method of relieving transmission congestion by optimal rescheduling with multiple DGs using PSO," in *International Conference on Swarm, Evolutionary, and Memetic Computing*, 2014, pp. 396-408.

[103] H. Lu, M. Zhang, Z. Fei, and K. Mao, "Multi-objective energy consumption scheduling in smart grid based on Tchebycheff decomposition," *IEEE Transactions on Smart Grid*, vol. 6, pp. 2869-2883, 2015.

[104] N. Kamaraj, "Transmission congestion management using particle swarm optimization," *J. Electrical Systems,* vol. 7, pp. 54-70, 2011.

[105] S. Hassan, "*Transmission Line Overload Alleviation by Generation Rescheduling and Load Shedding in the National Grid of Sudan*," M. Sc. Thesis, Karary Academy of Technology, Sudan, 2005.

[106] M. E. Arini, "Fast method to alleviate line overloads by corrective generation rescheduling and load shedding," *Electric Machines and Power Systems*, vol. 25, pp. 355-370, 1997.

[107] A. S. Korad and K. W. Hedman, "Robust corrective topology control for system reliability," *IEEE Transactions on Power Systems,* vol. 28, pp. 4042-4051, 2013.

[108] P. A. Ruiz, J. M. Foster, A. Rudkevich, and M. C. Caramanis, "Tractable transmission topology control using sensitivity analysis," *IEEE Transactions on Power Systems,* vol. 27, pp. 1550-1559, 2012.

[109] K. W. Hedman, M. C. Ferris, R. P. O. Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Transactions on Power Systems,* vol. 25, pp. 1052-1063, 2010.

[110] A. Khodaei, M. Shahidehpour, and S. Kamalinia, "Transmission switching in expansion planning," *IEEE Transactions on Power Systems,* vol. 25, pp. 1722-1733, 2010.

[111] J. D. Fuller, R. Ramasra, and A. Cha, "Fast heuristics for transmission-line switching," *IEEE Transactions on Power Systems,* vol. 27, pp. 1377-1386, 2012.

[112] M. Soroush and J. D. Fuller, "Accuracies of optimal transmission switching heuristics based on DCOPF and ACOPF," *IEEE Transactions on Power Systems,* vol. 29, pp. 924-932, 2014.

[113] D. Patteeuw, G. P. Henze, and L. Helsen, "Comparison of load shifting incentives for low-energy buildings with heat pumps to attain grid flexibility benefits," *Applied Energy,* vol. 167, pp. 80-92, 2016.

[114] J. Tang, J. Liu, F. Ponci, and A. Monti, "Adaptive load shedding based on combined frequency and voltage stability assessment using synchrophasor measurements," *IEEE Transactions on Power Systems,* vol. 28, pp. 2035-2047, 2013.

[115] C. W. Taylor, "Concepts of undervoltage load shedding for voltage stability," *IEEE transactions on Power Delivery,* vol. 7, pp. 480-488, 1992.

[116] P. Siano, "Demand response and smart grids—A survey," *Renewable and Sustainable Energy Reviews,* vol. 30, pp. 461-478, 2014.

[117] S. Nolan and M. O′Malley, "Challenges and barriers to demand response deployment and evaluation," *Applied Energy,* vol. 152, pp. 1-10, 2015.

[118] P. Pinson and H. Madsen, "Benefits and challenges of electrical demand response: A critical review," *Renewable and Sustainable Energy Reviews,* vol. 39, pp. 686-699, 2014.

[119] P. Cappers, C. Goldman, and D. Kathan, "Demand response in US electricity markets: Empirical evidence," *Energy,* vol. 35, pp. 1526-1535, 2010.

[120] R. M. Sasiraja, V. S. Kumar, and S. Ponmani, "An elegant emergence of optimal siting and sizing of multiple distributed generators used for

transmission congestion relief," *Turkish Journal of Electrical Engineering & Computer Sciences,* vol. 23, pp. 1882-1895, 2015.

[121] F. Luo, J. Zhao, J. Qiu, J. Foster, Y. Peng, and Z. Dong, "Assessing the transmission expansion cost with distributed generation: An Australian case study," *IEEE Transactions on Smart Grid,* vol. 5, pp. 1892-1904, 2014.

[122] C. Liu, J. Wang, A. Botterud, Y. Zhou, and A. Vyas, "Assessment of impacts of PHEV charging patterns on wind-thermal scheduling by stochastic unit commitment," *IEEE Transactions on Smart Grid,* vol. 3, pp. 675-683, 2012.

[123] D. T.-C. Wang, L. F. Ochoa, and G. P. Harrison, "DG impact on investment deferral: Network planning and security of supply," *IEEE Transactions on Power Systems,* vol. 25, pp. 1134-1141, 2010.

[124] H. A. Gil and G. Joos, "On the quantification of the network capacity deferral value of distributed generation," *IEEE Transactions on Power Systems,* vol. 21, pp. 1592-1599, 2006.

[125] J. Després, S. Mima, A. Kitous, P. Criqui, N. Hadjsaid, and I. Noirot, "Storage as a flexibility option in power systems with high shares of variable renewable energy sources: a POLES-based analysis," *Energy Economics,* vol. 64, pp. 638-650, 2017.

[126] Y. Sun, Z. Li, M. Shahidehpour, and B. Ai, "Battery-based energy storage transportation for enhancing power system economics and security," *IEEE Transactions on Smart Grid,* vol. 6, pp. 2395-2402, 2015.

[127] J. Hu, S. You, M. Lind, and J. Ostergaard, "Coordinated charging of electric vehicles for congestion prevention in the distribution grid," *IEEE Transactions on Smart Grid,* vol. 5, pp. 703-711, 2014.

[128] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle-to-grid energy and ancillary services," *IEEE Transactions on Smart Grid,* vol. 3, pp. 351-359, 2012.

[129] N. S. Hasan, M. Y. Hassan, M. S. Majid, and H. A. Rahman, "Review of storage schemes for wind energy systems," *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 237-247, 2013.

[130] S. Sundararagavan and E. Baker, "Evaluating energy storage technologies for wind power integration," *Solar Energy,* vol. 86, pp. 2707-2717, 2012.

[131] K. Singh, V. K. Yadav, N. P. Padhy, and J. Sharma, "Congestion management considering optimal placement of distributed generator in deregulated power system networks," *Electric Power Components and Systems,* vol. 42, pp. 13-22, 2014.

[132] S. Koohi-Kamali, V. Tyagi, N. Rahim, N. Panwar, and H. Mokhlis, "Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review," *Renewable and Sustainable Energy Reviews,* vol. 25, pp. 135-165, 2013.

[133] K. Divya and J. Østergaard, "Battery energy storage technology for power systems—An overview," *Electric Power Systems Research,* vol. 79, pp. 511-520, 2009.

[134] L. S. Vargas, G. Bustos-Turu, and F. Larraín, "Wind power curtailment and energy storage in transmission congestion management considering power

plants ramp rates," *IEEE Transactions on Power Systems*, vol. 30, pp. 2498-2506, 2015.

[135] J. Li, F. Cai, L. Qiao, J. Wang, H. Gao, W. Tang, P. Peng, D. Geng, X. Li, Q. Li "China wind power review and outlook," *Global Wind Energy Council: Brussels, Belgium*, 2014. http://www.gwec.net/wp-content/uploads/2012/06/2014%E9%A3%8E%E7%94%B5%E6%8A%A5%E5%91%8A2%E8%8B%B1%E6%96%87-20150317.pdf Retrived 20/10/2016

[136] G. Papaefthymiou, K. Grave, and K. Dragoon, "Flexibility options in electricity systems," *Project number: POWDE14426, Ecofys*, 2014. http://www.ecofys.com /en/ press/report- flexibility-options-in-electricity-systems/ Retrived 10/10/2016

[137] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. PortilloGuisado, M. M. Prats, *et al.*, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Transactions on Industrial Electronics*, vol. 53, pp. 1002-1016, 2006.

[138] N. Acharya, A. Sode-Yome, and N. Mithulananthan, "Facts about flexible AC transmission systems (FACTS) controllers: practical installations and benefits," in *Australasian Universities Power Engineering Conference (AUPEC), Australia*, 2005, pp. 533-538.

[139] K. Padiyar, *Structure Preserving Energy Functions in Power Systems: Theory and Applications*. Boca Raton: CRC Press, 2013.

[140] M. Zakarya, "SMART GRIDS: A prologue & unscrew challenges that needs to be addressed, A Short Survey on how to make Grids Smarter," *VAWKUM Transactions on Computer Sciences*, vol. 1, pp. 1-9, 2013.

[141] P. Jirapong and W. Ongsakul, "Optimal placement of multi-type FACTS devices for total transfer capability enhancement using hybrid evolutionary algorithm," *Electric Power Components and Systems*, vol. 35, pp. 981-1005, 2007.

[142] M. Castro, H. Ayres, V. Da Costa, and L. Da Silva, "Impacts of the SSSC control modes on small-signal and transient stability of a power system," *Electric Power Systems Research*, vol. 77, pp. 1-9, 2007.

[143] L. Rajalakshmi, M. Suganyadevi, and S. Parameswari, "Congestion management in deregulated power system by locating series FACTS devices," *International Journal of Computer Applications*, vol. 13, pp. 19-22, 2011.

[144] A. W. Bhutto, A. A. Bazmi, and G. Zahedi, "Greener energy: Issues and challenges for Pakistan—wind power prospective," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 519-538, 2013.

[145] J. Matevosyan and L. Söder, "Short-term hydropower planning coordinated with wind power in areas with congestion problems," *Wind Energy*, vol. 10, pp. 195-208, 2007.

[146] M. Gitizadeh, "Allocation of multi-type FACTS devices using multi-objective genetic algorithm approach for power system reinforcement," *Electrical Engineering (Archiv fur Elektrotechnik)*, vol. 92, pp. 227-237, 2010.

[147] B. Bhattacharyya and S. Kumar, "Loadability enhancement with FACTS devices using gravitational search algorithm," *International Journal of Electrical Power & Energy Systems,* vol. 78, pp. 470-479, 2016.

[148] M. Saravanan, S. M. R. Slochanal, P. Venkatesh, and J. P. S. Abraham, "Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability," *Electric Power Systems Research,* vol. 77, pp. 276-283, 2007.

[149] Y. Zhang and J. V. Milanovic, "Global voltage sag mitigation with FACTS-based devices," *IEEE Transactions on Power Delivery,* vol. 25, pp. 2842-2850, 2010.

[150] R. K. Varma, S. Auddy, and Y. Semsedini, "Mitigation of subsynchronous resonance in a series-compensated wind farm using FACTS controllers," *IEEE Transactions on Power Delivery,* vol. 23, pp. 1645-1654, 2008.

[151] N. Acharya and N. Mithulananthan, "Locating series FACTS devices for congestion management in deregulated electricity markets," *Electric Power Systems Research,* vol. 77, pp. 352-360, 2007.

[152] F. Galiana, K. Almeida, M. Toussaint, J. Griffin, D. Atanackovic, B. Ooi*, et al.*, "Assessment and control of the impact of FACTS devices on power system performance," *IEEE Transactions on Power Systems,* vol. 11, pp. 1931-1936, 1996.

[153] V. Roberge, M. Tarbouchi, and F. Okou, "Optimal power flow based on parallel metaheuristics for graphics processing units," *Electric Power Systems Research,* vol. 140, pp. 344-353, 2016.

[154] H. Saadat, *Power system analysis*. New York: McGraw-Hill, 1999.

[155] Q. Song, W. Liu, X. Li, H. Rao, S. Xu, and L. Li, "A steady-state analysis method for a modular multilevel converter," *IEEE Transactions on Power electronics,* vol. 28, pp. 3702-3713, 2013.

[156] J. Qin and M. Saeedifard, "Predictive control of a modular multilevel converter for a back-to-back HVDC system," *IEEE Transactions on Power delivery,* vol. 27, pp. 1538-1547, 2012.

[157] E. Acha, C. R. Fuerte-Esquivel, H. Ambriz-Perez, and C. Angeles-Camacho, *FACTS: modelling and simulation in power networks*. London: John Wiley & Sons, 2004.

[158] R. Marconato, *Electric Power Systems (Background and Basic Components)* Milan: CEI–Italian Electrotechnical Committee, 2002.

[159] M. S. Calovic, "Modeling and analysis of under-load tap-changing transformer control systems," *IEEE Transactions on Power Apparatus and Systems,* pp. 1909-1915, 1984

[160] H. E. Farag and E. F. El-Saadany, "A novel cooperative protocol for distributed voltage control in active distribution systems," *IEEE Transactions on Power Systems,* vol. 28, pp. 1645-1656, 2013.

[161] M. R. Shakarami and R. Sedaghati, "A Study on Integrated Performance of Tap-Changing Transformer and SVC in Association with Power System Voltage Stability," *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering,* vol. 8, pp. 1174-1181, 2014.

[162] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling, and R. Belmans, "Analytical approach to grid operation with phase shifting transformers," *IEEE Transactions on Power Systems*, vol. 23, pp. 41-46, 2008.

[163] W. Lyman, "Controlling power flow with phase shifting equipment," *Transactions of the American Institute of Electrical Engineers*, vol. 49, pp. 825-829, 1930.

[164] G. Migliavacca, *Advanced Technologies for Future Transmission Grids*. Heidelberg: Springer Science & Business Media, 2012.

[165] A. Marinakis, "*Multi-actor Optimization-based Coordination of Interacting Power Flow Control Devices or Competing Transaction Schedulers in Overlapping Electricity Markets*," PhD Thesis, Université de Liège, France, 2010.

[166] B. Kasztenny and E. Rosolowski, "Modeling and protection of hexagonal phase-shifting transformers—Part II: Protection," *IEEE Transactions on Power Delivery*, vol. 23, pp. 1351-1358, 2008.

[167] J. Verboomen, D. Van Hertem, P. H. Schavemaker, W. L. Kling, and R. Belmans, "Phase shifting transformers: principles and applications," in *Future Power Systems, 2005 International Conference on*, 2005, pp. 6 pp.-6.

[168] S. C. Müller, U. Häger, and C. Rehtanz, "A multiagent system for adaptive power flow control in electrical transmission systems," *IEEE Transactions on Industrial Informatics*, vol. 10, pp. 2290-2299, 2014.

[169] A. Marinakis, M. Glavic, and T. Van Cutsem, "Minimal reduction of unscheduled flows for security restoration: Application to phase shifter control," *IEEE Transactions on Power Systems*, vol. 25, pp. 506-515, 2010.

[170] B. Patel, H. Smith, T. Hewes, and W. Marsh, "Application of phase shifting transformers for Daniel-Mcknight 500kV interconnection," *IEEE Transactions on Power Delivery*, vol. 1, pp. 167-173, 1986.

[171] B. Asghari, M. O. Faruque, and V. Dinavahi, "Detailed real-time transient modelof the "Sen" transformer," *IEEE Transactions on Power Delivery*, vol. 23, pp. 1513-1521, 2008.

[172] S. Chanana and A. Kumar, "Comparison of Sen transformer and unified power flow controller on spot price variation of real and reactive power under maximum loadability condition," *Electric Power Components and Systems*, vol. 36, pp. 1369-1387, 2008.

[173] A. Merkhouf, P. Doyon, and S. Upadhyay, "Variable frequency transformer—Concept and electromagnetic design evaluation," *IEEE Transactions on Energy Conversion*, vol. 23, pp. 989-996, 2008.

[174] A. Merkhouf, S. Upadhyay, and P. Doyon, "Variable frequency transformer-an overview," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 4 pp.

[175] R. Piwko, E. Larsen, and C. Wegner, "Variable frequency transformer-a new alternative for asynchronous power transfer," in *Power Engineering Society Inaugural Conference and Exposition in Africa, 2005 IEEE*, 2005, pp. 393-398.

[176] M. Tolue Khayami, H. Shayanfar, and A. Kazemi, "Stability analysis of rotary power flow controller," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 28, pp. 442-455, 2015.

[177] A. O. Ba, T. Peng, and S. Lefebvre, "Rotary power-flow controller for dynamic performance evaluation—Part I: RPFC modeling," *IEEE Transactions on Power Delivery*, vol. 24, pp. 1406-1416, 2009.

[178] A. O. Ba, T. Peng, and S. Lefebvre, "Rotary power-flow controller for dynamic performance evaluation—Part II: RPFC application in a transmission corridor," *IEEE Transactions on Power Delivery*, vol. 24, pp. 1417-1425, 2009.

[179] E. V. Larsen, "Power flow control and power recovery with rotary transformers," U.S. Patent No. 5953225. Washington, DC: U.S. Patent and Trademark Office, 1999. Retrived 16/8/2016.

[180] E. V. Larsen, "Power flow control with rotary transformers," U.S. Patent No. 5841267. Washington, DC: U.S. Patent and Trademark Office, 1998. Retrived 16/8/2016.

[181] Z. Tan, C. Zhang, and Q. Jiang, "Research on characteristics and power flow control strategy of rotary power flow controller," in *Energy (IYCE), 2015 5th International Youth Conference on*, 2015, pp. 1-8.

[182] M. H. Abardeh and R. Ghazi, "Rotary power flow controller (RPFC) characteristics analysis," in *Power Engineering and Optimization Conference (PEOCO), 2011 5th International*, 2011, pp. 358-363.

[183] H. Fujita, S. Ihara, E. Larsen, E. Pratico, and W. Price, "Modeling and dynamic performance of a rotary power flow controller," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 599-604.

[184] H. Fujita, S. Ihara, E. Larsen, and W. Price, "Basic characteristics of a rotary power flow controller," in *Power Engineering Society Winter Meeting, 2000. IEEE*, 2000, pp. 1477-1482.

[185] H. Fujita, D. Baker, S. Ihara, E. Larsen, and W. Price, "Power flow controller using rotary phase-shifting transformers," in *CIGRE Session*, 2000, pp. 37-102.

[186] P. C. Sen, *Power electronics*. New Delhi: Tata McGraw-Hill Education, 1987.

[187] E. R. Pratico, C. Wegner, E. V. Larsen, R. J. Piwko, D. R. Wallace, and D. Kidd, "VFT operational overview-the Laredo project," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-6.

[188] M. Crappe, *Electric power systems*. Hoboken: John Wiley & Sons, 2013.

[189] E. H. Bayoumi, "Power electronics in smart grid power transmission systems: a review," *International Journal of Industrial Electronics and Drives*, vol. 2, pp. 98-115, 2015.

[190] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, *et al.*, "Smart transmission grid: Vision and framework," *IEEE Transactions on Smart Grid*, vol. 1, pp. 168-177, 2010

[191] L. F. W. de Souza, E. H. Watanabe, and J. E. da Rocha Alves Jr, "Thyristor and gate-controlled series capacitors: A comparison of components rating," *IEEE Transactions on Power Delivery*, vol. 23, pp. 899-906, 2008.

[192] A. Edris, "Proposed terms and definitions for flexible AC transmission system (FACTS)," *IEEE Transactions on Power Delivery*, vol. 12, 1997.

[193] L. Gyugyi, "Dynamic compensation of AC transmission lines by solid-state synchronous voltage sources," *IEEE Transactions on Power Delivery*, vol. 9, pp. 904-911, 1994.

[194] L. Gyugyi, "Solid-state control of electric power in ac transmission systems," in *International Symposium on Electric Energy Converters in Power Systems*, 1989.

[195] I. Khan, M. Mallick, M. Rafi, and M. S. Mirza, "Optimal placement of FACTS controller scheme for enhancement of power system security in Indian scenario," *Journal of Electrical Systems and Information Technology,* vol. 2, pp. 161-171, 2015.

[196] F. M. Albatsh, S. Mekhilef, S. Ahmad, H. Mokhlis, and M. Hassan, "Enhancing power transfer capability through flexible AC transmission system devices: a review," *Frontiers of Information Technology & Electronic Engineering,* vol. 16, pp. 658-678, 2015.

[197] R. M. Pereira, C. M. Ferreira, and F. M. Barbosa, "Comparative study of STATCOM and SVC performance on dynamic voltage collapse of an electric power system with wind generation," *IEEE Latin America Transactions,* vol. 12, pp. 138-145, 2014.

[198] A. L. Ara, A. Kazemi, and S. N. Niaki, "Multiobjective optimal location of FACTS shunt-series controllers for power system operation planning," *IEEE Transactions on Power Delivery,* vol. 27, pp. 481-490, 2012.

[199] M. Banaei and A. Kami, "Interline power flow controller (IPFC) based damping recurrent neural network controllers for enhancing stability," *Energy Conversion and Management,* vol. 52, pp. 2629-2636, 2011.

[200] Y. Xiao, Y. Song, and Y. Sun, "Power flow control approach to power systems with embedded FACTS devices," *IEEE Transactions on power systems,* vol. 17, pp. 943-950, 2002.

[201] T. Nireekshana, G. K. Rao, and S. S. Raju, "Available transfer capability enhancement with FACTS using Cat Swarm Optimization," *Ain Shams Engineering Journal,* vol. 7, pp. 159-167, 2016.

[202] T. Jain, S. Singh, and S. Srivastava, "Dynamic ATC enhancement through optimal placement of FACTS controllers," *Electric Power Systems Research,* vol. 79, pp. 1473-1482, 2009.

[203] H. Sawhney and B. Jeyasurya, "Application of unified power flow controller for available transfer capability enhancement," *Electric Power Systems Research,* vol. 69, pp. 155-160, 2004.

[204] Y. Xiao, Y. Song, C.-C. Liu, and Y. Sun, "Available transfer capability enhancement using FACTS devices," *IEEE Transactions on Power Systems,* vol. 18, pp. 305-312, 2003.

[205] P. Acharjee, "Optimal power flow with UPFC using security constrained self-adaptive differential evolutionary algorithm for restructured power system," *International Journal of Electrical Power & Energy Systems,* vol. 76, pp. 69-81, 2016.

[206] L. Goel, Q. Wu, and P. Wang, "Fuzzy logic-based direct load control of air conditioning loads considering nodal reliability characteristics in restructured power systems," *Electric Power Systems Research,* vol. 80, pp. 98-107, 2010.

[207] H. L. Ferreira, A. L′Abbate, G. Fulli, and U. Häger, "Flexible Alternating Current Transmission Systems (FACTS) Devices," in *Advanced Technologies for Future Transmission Grids,* ed: Springer, 2013, pp. 119-156.

[208] N. G. Hingorani, "Role of FACTS in a deregulated market," in *Power Engineering Society Summer Meeting, 2000. IEEE*, 2000, pp. 1463-1467.

[209] S. K. Kodsi, C. A. Canizares, and M. Kazerani, "Reactive current control through SVC for load power factor correction," *Electric Power Systems Research,* vol. 76, pp. 701-708, 2006.

[210] R. M. Mathur and R. K. Varma, *Thyristor-based FACTS Controllers for Electrical Transmission Systems*. Piscataway: John Wiley & Sons, 2002.

[211] M. Noroozian, "Modelling of SVC in power system studies," *Published by ABB Power Systems, Reactive Power Compensation Division, Vasteras, Sweden,* 2006.

[212] B. Singh, R. Saha, A. Chandra, and K. Al-Haddad, "Static synchronous compensators (STATCOM): a review," *IET Power Electronics,* vol. 2, pp. 297-324, 2009.

[213] Y. Ye, M. Kazerani, and V. H. Quintana, "Current-source converter based STATCOM: Modeling and control," *IEEE Transactions on Power Delivery,* vol. 20, pp. 795-800, 2005.

[214] C. A. Canizares, M. Pozzi, S. Corsi, and E. Uzunovic, "STATCOM modeling for voltage and angle stability studies," *International Journal of Electrical Power & Energy Systems,* vol. 25, pp. 431-441, 2003.

[215] Z. Yang, M. L. Crow, C. Shen, and L. Zhang, "The steady state characteristics of a StatCom with energy storage," in *Power Engineering Society Summer Meeting, 2000. IEEE,* 2000, pp. 669-674.

[216] J. Ainsworth, M. Davies, P. Fitz, K. Owen, and D. Trainer, "Static var compensator (STATCOM) based on single-phase chain circuit converters," *IEE Proceedings-Generation, Transmission and Distribution,* vol. 145, pp. 381-386, 1998.

[217] A. H. Norouzi and A. Sharaf, "Two control schemes to enhance the dynamic performance of the STATCOM and SSSC," *IEEE Transactions on Power Delivery,* vol. 20, pp. 435-442, 2005.

[218] K. Padiyar, *FACTS Controllers in Power Transmission and Distribution*. New Delhi: New Age International, 2007.

[219] Z. Mao, "A new modeling and control scheme for thyristor-controlled series capacitor," *Journal of Control Theory and Applications,* vol. 7, pp. 81-86, 2009.

[220] D. Jovcic and G. Pillai, "Analytical modeling of TCSC dynamics," *IEEE Transactions on Power Delivery,* vol. 20, pp. 1097-1104, 2005.

[221] C. Fuerte-Esquivel, E. Acha, and H. Ambriz-Perez, "A thyristor controlled series compensator model for the power flow solution of practical power networks," *IEEE Transactions on Power Systems,* vol. 15, pp. 58-64, 2000.

[222] S. Musunuri and G. Dehnavi, "Comparison of STATCOM, SVC, TCSC, and SSSC performance in steady state voltage stability improvement," in *North American Power Symposium (NAPS), 2010*, 2010, pp. 1-7.

[223] L. Ängquist, G. Ingeström, and H.-Å. Jönsson, "Dynamical performance of TCSC schemes," *ABB Power Systems AB, Sweden, CIGRÉ*, pp. 14-302, 1996.

[224] Y. Zhang and Y. Zhang, "A novel power injection model of embedded SSSC with multi-control modes for power flow analysis inclusive of practical constraints," *Electric Power Systems Research*, vol. 76, pp. 374-381, 2006.

[225] M. El-Moursi and A. Sharaf, "Novel controllers for the 48-pulse VSC STATCOM and SSSC for voltage regulation and reactive power compensation," *IEEE Transactions on Power systems,* vol. 20, pp. 1985-1997, 2005.

[226] K. K. Sen, "SSSC-static synchronous series compensator: theory, modeling, and application," *IEEE Transactions on Power Delivery,* vol. 13, pp. 241-246, 1998.

[227] L. Gyugyi, C. D. Schauder, and K. K. Sen, "Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines," *IEEE Transactions on Power Delivery,* vol. 12, pp. 406-417, 1997.

[228] X.-P. Zhang, C. Rehtanz, and B. Pal, *Flexible AC Transmission Systems: Modelling and Control*. Heidelberg: Springer Science & Business Media, 2012.

[229] V. Stel′Makov, V. Zhmurov, and A. Tarasov, "Thyristor-controlled phase-shifting devices," *Russian Electrical Engineering,* vol. 85, pp. 10-17, 2014.

[230] X. Kai and G. Kusic, "Application of thyristor-controlled phase shifters to minimize real power losses and augment stability of power systems," *IEEE Transactions on Energy Conversion,* vol. 3, pp. 792-798, 1988.

[231] D. Divan and H. Johal, "Distributed FACTS—A new concept for realizing grid power flow control," *IEEE Transactions on Power Electronics,* vol. 22, pp. 2253-2260, 2007.

[232] F. Kreikebaum, D. Das, Y. Yang, F. Lambert, and D. Divan, "Smart wires — A distributed, low-cost solution for controlling power flows and monitoring transmission lines," in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES,* 2010, pp. 1-8.

[233] A. Elmitwally, "Smart-wire approach for upgrading power systems with wind generation," *Int Rev Autom Control (Theor Appl),* vol. 5, pp. 498-505, 2012.

[234] F. Kreikebaum, M. Imayavaramban, and D. Divan, "Active smart wires: An inverter-less static series compensator," in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE,* 2010, pp. 3626-3630.

[235] D. Das, F. Kreikebaum, D. Divan, and F. Lambert, "Reducing transmission investment to meet renewable portfolio standards using smart wires," in *Transmission and Distribution Conference and Exposition, 2010 IEEE PES,* 2010, pp. 1-7.

[236] R. Sadiković, "*Use of FACTS Devices for Power Flow Control and Damping of Oscillations in Power Systems*," Doctor of Technical Sciences Thesis, Swiss Federal Institute of Technology Zurich, Switzerland, 2006.

[237] B. Zhang and Q. Ding, "The development of FACTS and its control," *International Conference on Advances in Power System Control, Operation and Management, APSCOM-97*, 1997, pp. 48 – 53.

[238] D. Murali, M. Rajaram, and N. Reka, "Comparison of FACTS devices for power system stability enhancement," *International Journal of Computer Applications,* vol. 8, pp. 30-35, 2010.

[239] L. Gyugyi, C. Schauder, S. Williams, T. Rietman, D. Torgerson, and A. Edris, "The unified power flow controller: A new approach to power transmission control," *IEEE Transactions on Power Delivery,* vol. 10, pp. 1085-1097, 1995.

[240] I. Papic, P. Zunko, D. Povh, and M. Weinhold, "Basic control of unified power flow controller," *IEEE Transactions on Power Systems,* vol. 12, pp. 1734-1739, 1997.

[241] A. L. Ara, J. Aghaei, M. Alaleh, and H. Barati, "Contingency-based optimal placement of Optimal Unified Power Flow Controller (OUPFC) in electrical energy transmission systems," *Scientia Iranica,* vol. 20, pp. 778-785, 2013.

[242] A. L. Ara, A. Kazemi, and M. Behshad, "Improving power systems operation through multiobjective optimal location of optimal unified power flow controller," *Turkish Journal of Electrical Engineering & Computer Sciences,* vol. 21, pp. 1893-1908, 2013.

[243] A. L. Ara, A. Kazemi, and S. N. Niaki, "Modelling of optimal unified power flow controller (OUPFC) for optimal steady-state performance of power systems," *Energy Conversion and Management,* vol. 52, pp. 1325-1333, 2011.

[244] R. P. Singh, S. Bharadwaj, and R. Singh, "Flexible AC transmission system controllers: A state of art," *International Journal of Electronic and Electrical Engineering,* vol. 7, pp. 843-850, 2014.

[245] J. Singh, S. Singh, and V. Pant, "Modeling of generalized unified power flow controller for suitable location and power flow control," *Iranian Journal of Electrical and Computer Engineering,* vol. 3, p. 103, 2004.

[246] X.-P. Zhang, E. Handschin, and M. Yao, "Modeling of the generalized unified power flow controller (GUPFC) in a nonlinear interior point OPF," *IEEE Transactions on Power Systems,* vol. 16, pp. 367-373, 2001.

[247] A. U. Rani and B. R. Reddy, "Modeling and Digital Simulation of InterlinePower Flow Controller System," *International Journal of Computer and Electrical Engineering,* vol. 2, p. 441, 2010.

[248] R. L. Vasquez-Arnez and L. C. Zanetta, "A novel approach for modeling the steady-state VSC-based multiline FACTS controllers and their operational constraints," *IEEE Transactions on Power Delivery,* vol. 23, pp. 457-464, 2008.

[249] L. Gyugyi, K. K. Sen, and C. D. Schauder, "The interline power flow controller concept: a new approach to power flow management in transmission systems," *IEEE Transactions on Power Delivery,* vol. 14, pp. 1115-1123, 1999.

[250] J. Monteiro, J. F. Silva, S. F. Pinto, and J. Palma, "Linear and sliding-mode control design for matrix converter-based unified power flow controllers," *IEEE Transactions on Power Electronics,* vol. 29, pp. 3357-3367, 2014.

[251] J. Monteiro, J. F. Silva, S. Pinto, and J. Palma, "Matrix converter-based unified power-flow controllers: Advanced direct power control method," *IEEE Transactions on Power Delivery,* vol. 26, pp. 420-430, 2011.

[252] Z. Yuan, S. W. de Haan, J. B. Ferreira, and D. Cvoric, "A FACTS device: Distributed power-flow controller (DPFC)," *IEEE Transactions on Power Electronics,* vol. 25, pp. 2564-2572, 2010.

[253] F. Z. Peng, Y. Liu, S. Yang, S. Zhang, D. Gunasekaran, and U. Karki, "Transformer-less unified power-flow controller using the cascade multilevel

inverter," *IEEE Transactions on Power Electronics,* vol. 31, pp. 5461-5472, 2016.

[254] Peng F. Z., & Mitra j. Transformerless unified power flow controller, case study, Michigan State University http://www.egr.msu.edu/pelab/projects/TUPFC%20 case%20study%20insert.pdf Retrieved 14 August 2016.

[255] T. Friedli, J. W. Kolar, J. Rodriguez, and P. W. Wheeler, "Comparative evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems," *IEEE Transactions on Industrial Electronics,* vol. 59, pp. 4487-4510, 2012.

[256] F. Z. Peng, S. Zhang, S. Yang, D. Gunasekaran, and U. Karki, "Transformer-less unified power flow controller using the cascade multilevel inverter," in *Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), 2014 International*, 2014, pp. 1342-1349.

[257] S. Dawn and P. K. Tiwari, "Improvement of economic profit by optimal allocation of TCSC & UPFC with wind power generators in double auction competitive power market," *International Journal of Electrical Power & Energy Systems,* vol. 80, pp. 190-201, 2016.

[258] K. Habur and D. O′Leary, "FACTS-flexible alternating current transmission systems: for cost effective and reliable transmission of electrical energy," *Siemens-World Bank Document–Final Draft Report, Erlangen*, 2004. https://www.scribd.com/document/86050846/FACTS-for-Cost-Effective-and-Reliable-Transmission-of-Electrical-Energy Retived 13/9/2016.

[259] A. Sode-Yome and N. Mithulananthan, "Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement," *International Journal of Electrical Engineering Education,* vol. 41, pp. 158-171, 2004.

[260] P. Venet, F. Perisse, M. El-Husseini, and G. Rojat, "Realization of a smart electrolytic capacitor circuit," *IEEE Industry Applications Magazine,* vol. 8, pp. 16-20, 2002.

[261] V. G. Mathad, B. F. Ronad, and S. H. Jangamshetti, "Review on comparison of FACTS controllers for power system stability enhancement," *International Journal of Scientific and Research Publications,* vol. 3, pp. 2250-315, 2013.

[262] E. Larson and T. Weaver, "FACTS overview," *IEEE/CIGRE,* vol. 108, 1995.

[263] X.-F. Wang, Y. Song, and M. Irving, *Modern Power Systems Analysis*. New York: Springer Science & Business Media, 2010.

[264] S. Ravindra, C. V. Suresh, S. Sivanagaraju, and V. V. Reddy, "Power system security enhancement with unified power flow controller under multi-event contingency conditions," *Ain Shams Engineering Journal,* vol. 8, pp. 9-28, 2017.

[265] D. Das, D. M. Divan, and R. G. Harley, "Power flow control in networks using controllable network transformers," *IEEE Transactions on Power Electronics,* vol. 25, pp. 1753-1760, 2010.

[266] D. Divan and J. Sastry, "Controllable network transformers," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, 2008, pp. 2340-2345.

[267] D. M. Divan and A. Prasai, "Compact dynamic phase angle regulators," USA Patent US 13/707,558, 2015.

[268] M. Iravani and D. Maratukulam, "Review of semiconductor-controlled (static) phase shifters for power systems applications," *IEEE Transactions on Power Systems*, vol. 9, pp. 1833-1839, 1994.

[269] H. Stemmler and G. Guth, "The thyristor-controlled static phase-shifter-A new tool for power flow-control in AC transmission-systems," *Brown Boveri Review*, vol. 69, pp. 73-78, 1982.

[270] A. A. Afzalian, S. A. N. Niaki, M. R. Iravani, and W. Wonham, "Discrete-event systems supervisory control for a dynamic flow controller," *IEEE Transactions on Power Delivery*, vol. 24, pp. 219-230, 2009.

[271] A. R. Iyer, R. P. Kandula, R. Moghe, J. E. Hernandez, F. C. Lambert, and D. Divan, "Validation of the plug-and-play ac/ac power electronics building block (AC-PEBB) for medium-voltage grid control applications," *IEEE Transactions on Industry Applications*, vol. 50, pp. 3549-3557, 2014.

[272] D. Divan, J. Sastry, A. Prasai, and H. Johal, "Thin AC converters—A new approach for making existing grid assets smart and controllable," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, 2008, pp. 1695-1701.

[273] D. Das, R. P. Kandula, J. A. Muñoz, D. Divan, R. G. Harley, and J. E. Schatz, "An integrated controllable network transformer—Hybrid active filter system," *IEEE Transactions on Industry Applications*, vol. 51, pp. 1692-1701, 2015.

[274] D. M. Divan and J. Sastry, "Voltage synthesis using dual virtual quadrature sources—A new concept in AC power conversion," *IEEE Transactions on Power Electronics*, vol. 23, pp. 3004-3013, 2008.

[275] R. Kandula, A. Prasai, H. Chen, R. Mayor, F. Lambert, T. Heidel, *et al.*, "Design considerations and experimental results for a 12.47-kV 3-phase 1 MVA power router," in *Energy Conversion Congress and Exposition (ECCE), 2015 IEEE*, 2015, pp. 5000-5007.

[276] L. Liu, P. Zhu, Y. Kang, and J. Chen, "Power-flow control performance analysis of a unified power-flow controller in a novel control scheme," *IEEE Transactions on Power Delivery*, vol. 22, pp. 1613-1619, 2007.

[277] Q. Li, "*Analysis, Design, and Laboratory Evaluation of a Distributed Unified Power Flow Controller Concept*," PhD Thesis, University of Kentucky, US, 2006.

[278] E. Gholipour and S. Saadate, "Improving of transient stability of power systems using UPFC," *IEEE Transactions on Power Delivery*, vol. 20, pp. 1677-1682, 2005.

[279] P. Szcześniak, J. Kaniewski, and M. Jarnut, "AC–AC power electronic converters without DC energy storage: A review," *Energy Conversion and Management*, vol. 92, pp. 483-497, 2015.

[280] P. Szcześniak and J. Kaniewski, "Power electronics converters without DC energy storage in the future electrical power network," *Electric Power Systems Research*, vol. 129, pp. 194-207, 2015.

[281] V. Mehta, M. Ayalani, and Y. Bhavsar, "Pulse width modulated single phase AC chopper for passive RL load," in *Engineering (NUiCONE), 2013 Nirma University International Conference on*, 2013, pp. 1-6.

[282] M. H. Rashid, *Power Electronics Handbook: Devices, Circuits and Applications*. London: Academic Press, 2010.

[283] A. Mozdzer and B. K. Bose, "Three-phase AC power control using power transistors," *IEEE Transactions on Industry Applications*, pp. 499-505, 1976.

[284] A. K. Sahoo, J. Meenakshi, S. Dash, and T. Thyagarajan, "Analysis and simulation of matrix converter using PSIM," in *Power Electronics, 2007. ICPE'07. 7th Internatonal Conference on*, 2007, pp. 414-419.

[285] N. A. Ahmed, K. Amei, and M. Sakui, "AC chopper voltage controller-fed single-phase induction motor employing symmetrical PWM control technique," *Electric Power Systems Research*, vol. 55, pp. 15-25, 2000.

[286] K. Koiwa and J.-I. Itoh, "A maximum power density design method for nine switches matrix converter using sic-mosfet," *IEEE Transactions on Power Electronics*, vol. 31, pp. 1189-1202, 2016.

[287] L. Empringham, J. W. Kolar, J. Rodriguez, P. W. Wheeler, and J. C. Clare, "Technological issues and industrial application of matrix converters: A review," *IEEE Transactions on Industrial Electronics*, vol. 60, pp. 4260-4271, 2013.

[288] A. Daniels and D. Slattery, "New power convertor technique employing power transistors," in *Proceedings of the Institution of Electrical Engineers*, 1978, pp. 146-150.

[289] L. Gyugyi and B. R. Pelly, *Static Power Frequency Changers: Theory, Performance, and Application*. Sheboygan: John Wiley & Sons, 1976.

[290] B.-H. Kwon, B.-D. Min, and J.-H. Kim, "Novel topologies of AC choppers," *IEE Proceedings-Electric Power Applications*, vol. 143, pp. 323-330, 1996.

[291] L. Salazar and E. Wiechmann, "On the characteristics of a PWM ac controller using four switches," in *Power Electronics Specialists Conference, 1993. PESC'93 Record., 24th Annual IEEE*, 1993, pp. 307-313.

[292] G. Joos and P. Ziogas, "A PWM ac controller-based high current power supply," in *Industrial Electronics, Control, Instrumentation, and Automation, 1992. Power Electronics and Motion Control., Proceedings of the 1992 International Conference on*, 1992, pp. 554-559.

[293] S. A. K. Bhat and J. Vithayathil, "A simple multiple pulsewidth modulated ac chopper," *IEEE Transactions on Industrial Electronics*, pp. 185-189, 1982.

[294] R. Langella and A. Testa, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," 2014. http://ieeexplore.ieee.org/document/6826459/ Retrived 15/8/2017

[295] W. Shockley, "The Theory of p-n junctions in semiconductors and p-n junction transistors," *Bell Labs Technical Journal*, vol. 28, pp. 435-489, 1949.

[296] H.-S. Lee, "High power bipolar junction transistors in silicon carbide," Licentiate Thesis, KTH, Stockholm, Sweden, 2005.

[297] V. Barkhordarian, "Power MOSFET basics," *Power Conversion and Intelligent Motion-English Edition*, vol. 22, 1996.

[298] Y. Li, A. Q. Huang, and K. Motto, "Experimental and numerical study of the emitter turn-off thyristor (ETO)," *IEEE Transactions on Power Electronics,* vol. 15, pp. 561-574, 2000.

[299] B. J. Baliga, M. S. Adler, R. P. Love, P. V. Gray, and N. D. Zommer, "The insulated gate transistor: A new three-terminal MOS-controlled bipolar power device," *IEEE Transactions on Electron devices,* vol. 31, pp. 821-828, 1984.

[300] B. Baliga, "Fast-switching insulated gate transistors," *IEEE Electron Device Letters,* vol. 4, pp. 452-454, 1983.

[301] T. K. Gachovska, "*Modeling of Power Semiconductor Devices*," PhD Thesis, The University of Nebraska-Lincoln, US, 2012.

[302] A. Blinov, D. Vinnikov, V. Ivakhno, and V. Zamaruev, "Hybrid IGBT-IGCT Switch," *Przegląd Elektrotechniczny,* vol. 88, pp. 12-15, 2012.

[303] V. K. Khanna, *Insulated Gate Bipolar Transistor IGBT Theory and Design*. Piscataway: John Wiley & Sons, 2004.

[304] A. A. Jaecklin, "Advanced power bipolar devices," in *Bipolar/BiCMOS Circuits and Technology Meeting, 1998. Proceedings of the 1998*, 1998, pp. 61-66.

[305] M. Ceraolo and D. Poli, *Fundamentals of Electric Power Engineering: from Electromagnetics to Power Systems*. Hoboken: John Wiley & Sons, 2014.

[306] C. Blake and C. Bull, "IGBT or MOSFET: choose wisely," *International Rectifier,* 2001.

[307] D. Yildirim and M. Bilgic, "PWM AC chopper control of single-phase induction motor for variable-speed fan application," in *Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE*, 2008, pp. 1337-1342.

[308] E. S. Loomis, *The Pythagorean Proposition*. Washington: National Council of Teachers of Mathematics, 1972.

[309] H. Coxeter and S. Greitzer, "*Geometry Revisited*," vol. 19 de MAA New Mathematical Library. Washington: The Mathematical Association of America, 1967.

[310] G. Gevay, "*An Axiomatic Approach to Geometry: Geometric Trilogy*,". Univ Szeged, Bolyai Institute Aradi Vertanuk Tere 1, 6720 Szeged, Hungary, 2017.

[311] T. Bassarear, *Mathematics for Elementary School Teachers*. Boston: Cengage Learning, 2011.

[312] M. L. Crowley, "The van Hiele model of the development of geometric thought," *Learning and Teaching Geometry, K-12,* pp. 1-16, 1987.

[313] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER's extensible optimal power flow architecture," in *Power & Energy Society General Meeting, 2009. PES'09. IEEE*, 2009, pp. 1-7.

[314] R. Zimmerman and D. Gan, "Matpower manual," *USA: PSERC Cornell Univ,* 1997. http://www.pserc.cornell.edu/matpower/manual.pdf Retrived 15/6/2014

[315] T. Kristiansen, "Utilizing matpower in optimal power flow," *Modeling, Identification and Control,* vol. 24, p. 49, 2003.

[316] S. Kamel, F. Jurado, and J. P. Lopes, "Comparison of various UPFC models for power flow control," *Electric Power Systems Research,* vol. 121, pp. 243-251, 2015.

[317] C. Fuerte-Esquivel and E. Acha, "Unified power flow controller: a critical comparison of Newton–Raphson UPFC algorithms in power flow studies," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 144, pp. 437-444, 1997.

[318] A. Nabavi-Niaki and M. R. Iravani, "Steady-state and dynamic models of unified power flow controller (UPFC) for power system studies," *IEEE Transactions on Power Systems*, vol. 11, pp. 1937-1943, 1996.

[319] G. W. Stagg and A. H. El-Abiad, *Computer Methods in Power System Analysis*. Auckland: McGraw-Hill, 1968.

[320] K. Shaarbafi, "Transformer Modelling Guide," *Teshmont Consultants LP*, 2014. https://www.aeso.ca/assets/linkfiles/4040.002-Rev02-Transformer-Modelling-Guide.pdf Retrived 1/1/2016

[321] G. T. Bellarmine and N. Arokiaswamy, "Energy Management techniques to meet power shortage problems in India," *Energy Conversion and Management*, vol. 37, pp. 319-328, 1996.

[322] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on Power Systems*, vol. 26, pp. 12-19, 2011.

[323] J. H. Harlow, *Electric Power Transformer Engineering*. Florida: CRC press, 2004.

[324] C. C. Liu, S. McArthur, and S. Lee, (Eds.), "*Smart Grid Handbook*" Chichester: John Wiley & Sons. 2016.

[325] R. S. Rao and V. S. Rao, "A generalized approach for determination of optimal location and performance analysis of FACTs devices," *International Journal of Electrical Power & Energy Systems*, vol. 73, pp. 711-724, 2015.

[326] K. Verma and H. Gupta, "Impact on real and reactive power pricing in open power market using unified power flow controller," *IEEE Transactions on Power Systems*, vol. 21, pp. 365-371, 2006.

[327] S. Singh and A. David, "Optimal location of FACTS devices for congestion management," *Electric Power Systems Research*, vol. 58, pp. 71-79, 2001.

[328] G. Ejebe and B. Wollenberg, "Automatic contingency selection," *IEEE Transactions on Power Apparatus and Systems*, pp. 97-109, 1979.

[329] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, *et al.*, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE Transactions on Power Systems*, vol. 19, pp. 1387-1401, 2004.

[330] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*. New York: John Wiley & Sons, 2012.