



Ain Shams University
Faculty of Engineering
Electrical Power and Machines Department

Power Network Performance Enhancement Using FACTS Applications

A Thesis
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Power Engineering

By

Ahmed Saad Kurdi

B. Sc., Electrical Engineering
(Power Engineering)
Cairo University, ١٩٩٦

Supervised By

Assoc.Prof.Dr. Abla Soliman Attia
Dr. Naggar Hassan Saad

Power & Machines Department
Faculty of Engineering
Ain Shams University

Cairo — ٢٠٠٧

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

STATEMENT

This dissertation is submitted to Ain Shams University for the degree of MASTER OF SCIENCE in Electrical Engineering.

The work included in this thesis is carried out by the author in the Department of Electrical Power and Machines, Faculty of Engineering, Ain Shams University, Egypt.

No part of this thesis has been submitted for the degree or a qualification at any other university or institution.

Thursday, October ٣١, ٢٠١٣

Signature:

Name: Ahmed Saad Kurdi

ACKNOWLEDGMENTS

First and foremost thanks to **ALLAH** The Most Beneficent and Most Merciful.

My sincerest gratitude to **Assoc.Prof.Dr. Abla Soliman Attia** for her excellent supervision, and encouragement shown during the period of this study.

I am deeply indebted **Dr. Naggat Hassan Saad** for his supervision, encouraging words and continuous guidance during this study.

I want to thank my inspiring colleagues at **PGESCO** Company, they are always helping me.

Finally, it gives me my great pleasure to express my sincere thanks to **my parents, my wife and my lovely daughters.**

Cairo

Thursday, October ٢١, ٢٠١٣

Ahmed kurdi

ABSTRACT

The rapid development of power electronics technology provides opportunities to develop new power equipment to improve the performance of the actual power systems. During the last decade, a number of control devices called “Flexible AC Transmission Systems” (FACTS) technology have been proposed and implemented. FACTS devices can be used for power flow control, voltage regulation, and enhancement of transient stability and damping of power oscillations.

The possibility to improve the performance of the AC transmission system utilizing power electronic equipment has been discussed a lot since about ten years. Some new semiconductor based concepts have been developed. The Thyristor Controlled Series Capacitor (TCSC) is one of such concept. By varying the inserted reactance, an immediate and well-defined impact on the active power flow in the transmission line is obtained. Several potential applications, specifically power oscillation damping, benefit from this capability. The concept implied the requirement to design a semiconductor valve, which can be inserted directly in the high-voltage power circuit. This certainly presented a technical challenge but the straightforward approach appeared to be a cost-effective alternative with small losses.

This thesis presents a detailed model of TCSC to study its effect on the enhancement of the power network performance. This study covers the network performance under steady-state and transient conditions. The model with PID controller is used to control the power flow during steady state operation and with stability controller to improve system stability during transient conditions. The MATLAB-Simulink-Toolbox is used to check the validity of the proposed model by applying it to a simple power network. Results of the simulated network, on which both controllers were implemented, are presented and show its effectiveness, and capability in controlling system variables during steady state and transient operations.

List Of Contents

	Page
Acknowledgements	I
Abstract	ii
List of Contents	iii
List of Figures	V
List of Acronyms	iX
List of Tables	Xi
Symbol Index	Xii
 Chapter 1 Introduction	 1
1.1 General	1
1.2 Thesis Objectives	3
1.3 Thesis Outline	3
 Chapter 2 FACTS Devices and Their Applications	 4
2.1 General	4
2.2 Flexible AC Transmission	4
2.3 Basic Principles Of Active And Reactive Power Flow Control	5
2.4 FACTS Controllers Categories	8
 CHAPTER 3 Reactive Power And TCSC	 13
3.1 General	13
3.2 Reactive Power	13
3.3 Impact Of Series Compensation Transmission Systems	17
3.4 Implementation Of Fixed Series Capacitors	20
3.5 Applications For Controlled Series Capacitors (CSC)	21
 CHAPTER 4 Simulation Study of Power Flow and Transient Stability	 26
4.1 General	26
4.2 Introduction And Typical Structure	26
4.3 The Thyristor Controlled Reactor (TCR)	27
4.4 Circuit Analysis And Operating Principles Of TCSC	32
4.5 Dynamical Model And Harmonics	35

٤,٦	TCSC Steady State And Dynamic Applications	٤٨
	CHAPTER ٥ Conclusions And Recommendations For Future Researches	٩٥
٥,١	Conclusion	٩٥
٥,٢	Future Recommendation	٩٥
	List of References	٩٨
	APPENDIX A	١٠٣

List of Figures

Fig. No.		Page
2,1	The basic idea of FACTS devices	5
2,2	Conventional Thyristor-based FACTS controllers	9
3,1	Magnetic field strength around a transmission line	14
3,2	Magnetic energy density around the line	14
3,3	Redistribution of magnetic field energy	15
3,4	Principle of shunt compensation	16
3,5	Principle of series compensation	17
3,6	Passive capacitor banks as temporary energy storage	17
3,7	Voltage versus power transfer to a passive node (B) lacking reactive Power support.	18
3,8	Power transfer versus terminal voltage angle separation for a line with rated voltage amplitude in both ends	19
3,9	Single line diagram of a series capacitor	20
3,10	Power flow control using CSC	21
3,11	Series compensated interconnection between two power systems.	22
3,12	Main circuit and valve current waveform for TSSC and TCSC	23
3,13	Photo of Imperatriz TCSC, Eletronorte, Brazil.	25
4,1	Simple Main Circuit of the TCSC	26
4,2	TCSC and transmission line model	28
4,3	TCSC and line model using Simulink program	29
4,4	Inductor current and voltage for $\alpha = 90^\circ$	29
4,5	inductor current and voltage for $\alpha = 120^\circ$	30
4,6	inductor current and voltage for $\alpha = 160^\circ$	31
4,7	Equivalent Reactance for the TCSC versus the Firing Angle	32
4,8	TCSC Power Frequency Steady-State Equivalent Reactance Characteristics	34
4,9	Line Current For $\alpha = 120^\circ$	35
4,10	Steady-State Inductor Current and Capacitor Voltage and Current For $\alpha = 120^\circ$	36
4,11	Fig. 4,11 Line Current For $\alpha = 160^\circ$	36
4,12	Steady-State Inductor and Capacitor Current For $\alpha = 160^\circ$	37
4,13	Steady-State Capacitor Voltage For $\alpha = 160^\circ$	37
4,14	FFT for Line Current for $\alpha = 100^\circ$	39
4,15	FFT for Capacitor Voltage Current for $\alpha = 100^\circ$	39
4,16	FFT for Line Current for $\alpha = 120^\circ$	40
4,17	FFT for Capacitor Voltage Current for $\alpha = 120^\circ$	40
4,18	FFT for Line Current for $\alpha = 130^\circ$	41

٤,١٩	FFT for Capacitor Voltage Current for $\alpha = ١٣.٠^\circ$	٤١
٤,٢٠	FFT for Line Current for $\alpha = ١٤.٠^\circ$	٤٢
٤,٢١	FFT for Capacitor Voltage Current for $\alpha = ١٤.٠^\circ$	٤٢
٤,٢٢	FFT for Capacitor Voltage Current for $\alpha = ١٤.٥^\circ$	٤٣
٤,٢٣	FFT for Line Current for $\alpha = ١٥.٠^\circ$	٤٤
٤,٢٤	FFT for Capacitor Voltage Current for $\alpha = ١٥.٠^\circ$	٤٤
٤,٢٥	FFT for Line Current for $\alpha = ١٦.٠^\circ$	٤٥
٤,٢٦	FFT for Capacitor Voltage Current for $\alpha = ١٦.٠^\circ$	٤٥
٤,٢٧	FFT for Line Current for $\alpha = ١٧.٠^\circ$	٤٦
٤,٢٨	FFT for Capacitor Voltage Current for $\alpha = ١٧.٠^\circ$	٤٦
٤,٢٩	FFT for Line Current for $\alpha = ١٧.٥^\circ$	٤٧
٤,٣٠	FFT for capacitor voltage current for $\alpha = ١٧.٥^\circ$	٤٧
٤,٣١	FFT for Capacitor Voltage and Line Current for Different Firing Angles.	٤٨
٤,٣٢	General Block Diagram Of The TCSC Model And External Control	٤٩
٤,٣٣	Single Line Diagram For System Under Study System	٥٠
٤,٣٤	Basic Control Scheme For The PI / PID Controller	٥١
٤.٥	System Tested With TCSC and Without PI Controller	٥٢
٤,٣٦	Bus (١) and (٢) Voltage with TCSC without PI controller	٥٢
٤,٣٧	Transmission Line ١ and ٢ Rms Current with TCSC without PI controller	٥٣
٤,٣٨	Machine ١ And ٢ Power Angle with TCSC without PI controller	٥٤
٤,٣٩	Equivalent reactance for the TCSC without PI controller	٥٤
٤,٤٠	Simulink model for the PI	٥٥
٤,٤١	System Under Study With TCSC With PI Controller and Reference Current Of ٨٤٧ Amp.	٥٦
٤,٤٢	Line ٢ Current RMS with PI Controller	٥٧
٤,٤٣	Machine ١ And ٢ Power in PU with PI Controller	٥٨
٤,٤٤	Machine ١ And ٢ Power angle with PI Controller	٥٨
٤,٤٥	TCSC Equivalent Reactance.	٥٩
٤,٤٦	Single Line Diagram For The Model Used In Simulation	٦٠
٤,٤٧	Power Block Set Diagram For The Model Used In Simulation	٦٠
٤,٤٨	Simulink model for the PID	٦٠
٤,٤٦	Line (١) and line (٢) RMS currents	٦١
٤,٤٧	Machine ١ electrical power output in PU	٦١
٤,٤٨	Machine ٢ electrical power output in PU	٦٢
٤,٤٩	Machine ١ Power Angle (deg)	٦٢

4,00	TCSC Equivalent Reactance	64
4,01	Bus-1 Voltage with and without PID	60
4,02	Bus-2 Voltage with and without PID	60
4,03	line 1 current with and without PID	66
4,04	Line 2 current with and without PID	66
4,05	Machine-1 Power Angle	67
4,06	Machine-2 Power Angle	67
4,07	the Two Machine-1 Power output	68
4,08	the Two Machine-2 Power output	68
4,09	TCSC Equivalent Reactance	69
4,10	Transfer function of the stability control loop	70
4,11	Single Machine-Infinite Bus System Example	71
4,12	Equal Area Criterion for Line Current Magnitude as an Input Signal	73
4,13	Equal Area criterion for active power flow as input signal	74
4,14	Set Point Variations	70
4,15	Simulink block diagram for system model used for simulation	70
4,16	Simulink Block Diagram For The Stability Controller	78
4,17	simulation results for BUS-1 voltage profile with TCSC and without TCSC	79
4,18	Simulation Results For BUS-2 Voltage Profile With TCSC And Without TCSC	80
4,19	Simulation Results for the Load Angle With TCSC And Without TCSC	80
4,20	Simulation Results for the Electrical Power Output for the Machine with TCSC And Without TCSC	81
4,21	Simulation Results TCSC Equivalent Reactance	81
4,22	Simulation Results For BUS-1 Voltage Profile With TCSC And Without TCSC	82
4,23	Simulation Results For BUS-2 Voltage Profile With TCSC And Without TCSC	83
4,24	Simulation results for the machine electrical power output with TCSC and without TCSC.	84
4,25	Simulation results for the load angle with TCSC and without TCSC	80
4,26	controller used for short circuit simulation	86
4,27	bus 1 voltage RMS with and without TCSC	87
4,28	bus 2 voltage RMS with and without TCSC	88
4,29	line 1 current RMS without TCSC	88
4,30	line 1 current with TCSC	89

ξ, ٨٢	Machine \ Load Angle without TCSC	٨٩
ξ, ٨٣	Machine \ Load Angle with TCSC	٩٠
ξ, ٨٤	Machine \ Load Angle With and Without TCSC	٩٠
ξ, ٨٥	Machine √ Load Angle without TCSC	٩١
ξ, ٨٦	Machine √ Load Angle with TCSC	٩١
ξ, ٨٧	Machine \ Electrical Power Output without TCSC	٩٢
ξ, ٨٨	Machine \ Electrical Power Output With And Without	٩٢
ξ, ٨٩	Machine √ Electrical Power Out	٩٣
ξ, ٩٠	Machine √ Electrical Power Output With and Without TCSC	٩٣
ξ, ٩١	TCSC's Equivalent Reactance	٩٤
ξ, ٩٢	TCSC's Equivalent Reactance	٩٤

.

List of Acronyms

Acronyms	Description
FACTS	Flexible AC Systems
PLL	Phase-Locked-Loop
PWM	Pulse-Width Modulation
POD	Power Oscillation Damping
QFT	Quantitative Feedback Theory
Rms	Root Mean Square
RLS	Recursive Least Square
SSR	Subsynchronous Resonance
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
SVR	Synchronous Voltage Reversal
TI	Tensional Interaction (SSR)
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controller Series Capacitor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Controller
VSC	Voltage-Source Converter
P.U	per unit
TCPAR	thyristor controlled phase angle reactor
GTO's	gate turn-off thyristor
FC-TCR	fixed capacitor with thyristor controlled reactor

SYMBOL INDEX

P	Active Power
$P_{\max}$	Maximum Active Power
Q	Reactive Power
$Q_{\max}$	Maximum Reactive Power
S	Complex, Active And Reactive Power
P_r	Receiving End Active Power
Q_r	Receiving End Reactive Power
P_s	Sending End Active Power
X	Transmission Line Impended
V_r	Receiving End Voltage
V_s	Sending End Voltage
δ	Power Angle
P_{comp}	Transmitted Power In Compensated
mH	Milli Henry
km	Kilo Meter
Hz	Hertz

List of Tables		
<u>Table No.</u>		Page
۲.۱	Summary of different FACTS Controllers	۱۲
۴.۱	Equivalent reactance (X_e)	۳۱
۴.۲	Total Harmonic Distortion Factors for TCSC	۳۸

CHAPTER (1)

INTRODUCTION

1.1 GENERAL

In today's highly complex and interconnected power systems, which is made of thousands of buses and hundreds of generators. So there is a great need to improve electric power utilization while still maintaining reliability and security.

Available power generation, usually not situated near a growing load center, is subject to regulatory policies and environmental issues. In order to meet the ever-growing power demand, utilities prefer to rely on already existing generation and power export/import arrangements instead of building new transmission lines that are subject to environmental and regulatory policies.

On the other hand, power flows in some of the transmission lines are well below their thermal limits, while certain lines are overloaded, which has an overall effect of deteriorating voltage profiles and decreasing system stability and security. In addition, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex, highly interconnected power systems.

This overall situation requires the review of traditional transmission methods and practices, and the creation of new concepts which would allow the use of existing generation and transmission lines up to their full capabilities without reduction in system stability and security. Another reason that is forcing the review of traditional transmission methods is the tendency of modern power systems to follow the changes in today's global economy that are leading to deregulation of electrical power markets in order to stimulate competition between utilities.

The desire to find solutions to these problems and limitations led to focused technological developments under the Flexible AC transmission system (FACTS) initiative of the Electric Power Research Institute (EPRI) in the United States with the ultimate objective to provide power electronics-based, real time control for transmission systems.

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

- i) Better utilization of existing transmission