Improvement of Voltage and Power Flow Control in the GCC Power Grid by using Coordinated FACTS Devices

submitted by

Tariq Masood

for the degree of Doctor of Philosophy

of the

University of Bath

Department of Electronic and Electrical Engineering

September, 2012

DEDICATED

To my beloved late wife **(IRSHAD BiBi 1974-2008)** for her unmatched support throughout my educational and professional career from 1984-2008. Unfortunately, I lost my beloved wife in a tragic road accident on 05/05/2008. This is an irreversible loss for whole my family.

May the departed soul rest in peace. (Ameen)

SPECIALTHANKS

I extend my special gratitude to my beloved **Mother and Father for their blessed prayers** for me and my family's continuous success and prosperity every time. Thanks for Almighty Allah bestow countless blessings for me and my family members.

Special thanks to my newly wife **Sajidan Perveen,** she did commendable job to bridge the gap as a new mother in particularly sharing love with a little Master. Abdullah Masood, Ali, Anus, Rehman and Mehwash Masood and of course new baby Master. Essa Masood.

I also extend my special thanks to my **Brothers and Sisters** and their family members, Arif & Rukhsan, Amjad & Khalida, Safdar & Amber and Suriay & Liaqat Ali.

ACKNOWLEDGEMENTS

First and foremost, this is a great pleasure to thank the many people who have helped me during my stay in the University of Bath time to time since 2001.

First and foremost, I am very grateful to my supervisors, **Professor Dr. Raj K. Aggarwal and Dr. Mil Redferen,** for their kind assistance and valuable discussions over the past three years and for all the time and efforts have put into this research work in all possible means. I have inspired for their value-added practical contribution, intellectual support and friendship. They have also shown a lot of endurance over the period of time. **WHEREAS, Professor Raj K. Aggarwal** has proven to be beacon of inspiration like a father and encouragement like a '*Light in the Tunnel*', without his tireless supervising efforts and support the completion of this project would undoubtedly not have been possible. His genuine concerns for all his colleagues and students "**wellbeing**" and cheerful are highly appreciated by everyone in the Center for Sustainable Power Distribution research group. It has truly been an honour for me to have worked with him. I thank **Professor Dr. Raj K. Aggarwal and Dr. Mil Redferen** for their guidance and encouragements throughout my time as a Ph.D student at the University of Bath, Bath, UK.

I am also very much indebted to the **Dr. Francis Robinson and Dr. Martin Balchin** (Transfer Panel Accessories') for their wonderful input on my transfer report. They have thoroughly reviewed and provided constructive recommendations against the findings to produce a high quality research work. I would like to pay special gratitude to the **Mr. Ken Bateup** for carefully proofreading my research work at University of Bath. This is an exceptional contribution to produce high quality work.

I would also like to thanks to **Mr. Nasser J. Al-Kuwari** (Manager Production, Dukhan Fields) and **Mr. Adel Amer El-Banna** (Asst. Manager Production Optimization, Dukhan Fields) and **Mr. Soud J. Al-Ruwaili** (Asst. Manager Operations RG Plant) for their unprecedented support, encouragement and exceptional endowment throughout my professional and education career with the Qatar Petroleum since 1997.

I would like to pay my special gratitude to my three mentors from the bottom of my heart, to the Adjunct **Professor Dr. Abdel-Ety Edris**, at Santa Clare University-USA and Director/Executive Advisor at Quanta Technology -USA , **Professor Dr. D.P Kothari** Director General Raisoni Group of Institution, Nagpur-India and **Professor Dr. Suhail Aftab Qureshi** Electrical Engineering Department at the University of Engineering and Technology Lahore Pakistan for their diligence support, guidance and time they have provided to read my thesis carefully during the review process. They have discussed multiple topics time to time and provided me recommendations against the findings in order to produce a high quality work.

At the last but not least I also pay my special gratitude to all my well-wishers in particularly, **Dr. Talib Hussain** Sial (former Admin DG to the President of Pakistan) **Advocate**. **Muhammad Syed. Ch** (Higher Courts Multan, Punjab), **Rana Khushi Muhammad** (DO Education, Sialkot), **Muhammad Amin.Ch** (Deputy Commissioner, Punjab), **Muhammad Arshid.Ch** (Admin officer at Pakistan Seed Corporation, Khanewal), and **Mahfooz Hussain** (Service Manager at the National Car Company Doha Qatar) for their wonderful moral support and encouragement throughout my educational and professional career.

I am also very thankful to the Mrs. Dorcas Mumford post graduate officer for her wonderful support and follow-up to complete my assignments and reports timely related to all aspects of the postgraduate research programmes at the University of Bath, Bath, UK.

ABSTRACT

This work presents HVDC/FACTS control device implementation framework in the Gulf cooperative council's countries. It comprises of five layers of FACTS control devices (STATCOM, SSSC, UPFC, HVDC and centralized/De-centralized Control). This five-layer architecture is designed in order to configure and produce the desired results; based on these outcomes, GCC power system network control and operational problems can be identified and addressed within the control architecture on the GCC power grid.

In the context of power FACTS-FRAME, this work is to identify and determine a number of power systems operational and control problems which are persistent on the GCC power grid e.g. poor voltage quality (SAG-Swell), poor load flow control, and limited power transfer capacity issues. The FACTS-FRAME is configured and synthesized by integrating multiple FACTS control devices (STATCOM, SSSC, UPFC) in parallel at different locations on the GCC power grid in order to meet stringent power system control and operational requirements with improved power transfer capacity, controllability and reliability.

The mathematical models are derived to indentify and determine operational constraints on the GCC power grid by incorporating real-time and estimated data and the acquired desired results. Herein, FACTS-FRAME is designed to handle distributed computation for intensive power system calculation by integrating multiple FACTS devices on multiple networks within the GCC power network. Distributed power flow algorithms are also derived in order to understand and implement centralized and decentralized control topologies as appropriate. The simulation results indicate the feasibility of FACTS devices implementation and their potential benefits under current operating conditions on the GCC power grid.

SIGNIFICANCE OF THIS RESEARCH WORK IN THE FIELD OF FACTS TECHNOLOGY

The FACTS technology has been developed to enhance the controllability of the synchronous power transmission system, thus permitting its operation closer to the stability limits. The basically different reasons for the existences of HVDC and FACTS have important consequences in the load flow solutions particularly. Therefore, firstly power electronic based controllers were introduced in the HVDC power transmission system for two purposes: regulation of power through HVDC link as well as for modulation to improve power system stability (both angle and voltage). Similarly, the FACTS controllers can be used to regulate power in critical power transmission lines and ease the congestion in the electrical power system network by adjusting time-based required shunt and series compensation. The major contributions of these devices are to provide continuous compensation within a couple of cycles. That is why the HVDC/FACTS devices have a strong impact to improve load flow, voltage quality and stability (both angular and voltage).

The first device is known as series compensation (SSSC). This device has a strong impact to improve stability (power angular and voltage) and is small on load flow and voltage quality. Second device is known as shunt compensation (STATCOM). This device has a strong impact on voltage quality and medium positive impact on power system stability (both angular and voltage). The third device is known as unified power flow control (UPFC/HVDC). As a contribution these devices have a strong impact on load flow, stability and voltage quality. By implementing these devices on the GCC power grid, we may witness flowing benefits.

- Enhanced existing power system transfer capacity on the GCC power grid
- Improved power system controllability and reliability on the GCC power grid
- Enhanced power system operational flexibility on the GCC power grid
- Addressing various equipment aging factors on the GCC power grid

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ABBREVIATIONS

The list below gives an overview of the notation frequently used in this thesis accompanied by a brief explanation and a page number of its definition or major occurrence.

Terms	:	Description	Page
GCC	:	Gulf cooperative council (Qatar, Oman, Bahrain, KSA, UAE, Kuwait)	
KSA	:	Kingdom of Saudi Arabia	
UAE	:	United Arab Emirates	
FACTS	:	Flexible AC transmission system	
STATCOM	:	Static synchronous compensator	104,105,116,117,130,131
SVC	:	Static Var compensator	104,105,116,117,130,131
FSC		Fixed series compensation	104,105,116,117,130,131
SSSC	:	Sub synchronous Series Controller	104,105,116,117,130,131
TCSC	:	Thyristor controlled series compensator	104,105,116,117,130,131
UPFC	:	Unified power flow controller	104,105,116,117,130,131
IPFC		Inter-phase power flow controller	34,104,105,116,117,130,131
TCVR	:	Thyristor controlled voltage regulator	34,104,105,116,117,130,131
TCPAR	:	Thyristor controlled phase angle regulator	34,104,105,116,117,130,131
TSSC	:	Thyristor switched series capacitor	34,104,105,116,117,130,131
GCSC	:	GTO Thyristor controlled series capacitor	34,104,105,116,117,130,131
Opex	:	Operating expenditure	104,105,116,117,130,131
Capex	:	Capital expenditure	104,105,116,117,130,131
HVDC	:	High voltage direct current	104,105,116,117,130,131
EHV	:	Extra High voltage	46
V_M	:	Midpoint voltage	52
I_Q	:	Current injected or draw to/from the AC system	52
Q_Q	:	Reactive power produced by the source	53
Q_L	:	Reactive power absorbs by the system	53
U_S	:	AC system voltage	59
U_C	:	Compensated voltage	59
SVS	:	Synchronous voltage source	60, 68
PWM		Pulse width modulation	28 & 68
PLL	:	Phase locked loop	80
G_L	:	Loop gain	80
G_T	:	Transmitter gain	80
G_C	:	Controller gain	80
G_V	:	Valve gain	80
G_P	:	Process gain	80
Ki	:	Integral gain (repeat per minute)	81
Ti	:	Integral time (minute per repeats)	82
PD	:	Derivative control	83
PID	:	Proportional, integral and derivative control.	84
OLT	:	Open loop tuning	84
CLT	:	Closed loop tuning	84
D_V	:	Deviation	86
E_P	:	Process error	86
Ku	:	Ultimate proportional gain	86

Terms	:	Description	Page
$CRV_{STATCOM}$	:	Credible value of STATCOM	98
CRV_{SSSC}	:	Credible value of SSSC	110
CRV_{UPFC}	:	Credible value of UPFC	121
Q	:	Reactive power	53, 54, 70
Iq_{ref}	:	Reactive current reference value	100, 112, 186
Iq_meaure	:	Reactive current measured value	
VSC	:	Voltage source converter	137, 149
CC1 & LC1	:	STATCOM's minimum capacitive and inductive compensation	47, 104, 166,184
CC11 & LC11	:	STATCOM's medium capacitive and inductive compensation	47, 104
CC111 & LC111	:	STATCOM's maximum capacitive and inductive compensation	47, 104
CC2 & LC2	:	SSSC's minimum capacitive and inductive compensation	88, 116
CC22 & LC22	:	SSSC's medium capacitive and inductive compensation	88, 116
CC222 & LC222	:	SSSC's maximum capacitive and inductive compensation	130,131
CC3 & CL3	:	UPFC's minimum capacitive and inductive compensation	130
CC33 & LC33	:	UPFC's medium capacitive and inductive compensation	130
CC333 & LC333	:	UPFC's maximum capacitive and inductive compensation	130
MCCR	:	Main central control room	154, 151
PWM	:	Pulse width modulation	28
MTRB	:	Metallic retune transfer breaker	146
WDB	:	Wideband Delphi	99
GA	:	Genetic Algorithm	104
DCS	:	Distributed Control System (Honeywell control)	144
SCADA	:	Supervisory control and data acquisition	144
APCS	:	Advance process control system	144
D1 & D2		Voltage and current measured location series part of the UPFC device in between Kuwait and KSA	160, 198, 199
D3 & D4		Voltage and current measured location shunt part of the UPFC device in between Kuwait and KSA	160, 198, 199
D5 & D6		Voltage and current measured location of the STATCOM device in between Bahrain and Qatar	160, 198, 199
D8 & D9		Voltage and current measured location of the SSSC device in between Oman and UAE	160, 198, 199

LIST OF PUBLICATIONS

Tariq Masood, R.K. Aggarwal, S.A. Qureshi, R.A.J Khan STATCOM and SVC Control Operations and Optimization during Network Fault Conditions: **IEEE International Symposium on Industrial Electronics Bari_ Italy (04-07 July, 2010).**
Online paper link: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5636868

Tariq Masood, R.K. Aggarwal, S.A. Qureshi, R.A.J Khan STATCOM Model against SVC Control Model Performance Analyses Technique by Matlab**: (ICREQP,10 Granada Spain 23-25 March,10). Online paper link: http://www.icrepq.com/icrepq'10/655-Masood.pdf**

Tariq Masood, R.K. Aggarwal, S.A. Qureshi, R.A.J Khan STATCOM Control Reconfiguration Technique for Steady State and Dynamic Performance Optimization during Network Fault Conditions: **(ICREQP,10 Granada Spain 23-25 March,10). Online paper link: http://www.icrepq.com/icrepq'10/656-Masood.pdf**

Tariq Masood, S. A Qureshi, A.j Khan, Nasser Elamedi, Yacob Y.Almulla, S K Shah “Facts Control Devices (Statcom, Sssc And Upfc) Re-Configuration Techniques By Psim/Matlab” **Papers published ICEE2007 on 11-12th April, 2007 at UET/RCET Lahore _ Pakistan**

Online paper link:
http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4287295&url=http%3A%2F%2Fieeexplore.ieee.org%2Fstamp%2Fstamp.jsp%3Ftp%3D%26arnumber%3D4287295

I have also produced numerous of papers on FACTS controllers, three of them are under consideration by the top ranking **IEEE** and **John Wiley & Sons** electrical power system transactions. I have received reviewer(s) findings and recommendations. These are addressed and approved successfully by my supervisor.

CHAPTER 1

Introduction

1.1 Problems to be investigated on the GCC power grid:

The GCC power transmission system is being pushed closer to its thermal and stability limits. The quality of power delivered has to be maintained which is also of a great concern. In fact power delivery limitations have many aspects and also involve power transfer between the areas on the GCC power network. The limitations of the power transmission system network can take numerous forms and may involve power transfer capability between areas on the GCC Power grid (Kuwait to KSA, Qatar to Bahrain, UAE to Oman) (referred to here as transmission bottlenecks) or within a single area or region (referred to here as a regional constraint)[16]. If there is limitation in between single areas or regions this is also known a regional constraint. The power transmission bottleneck and regional constraints may include the following characteristics on the Gulf Cooperative Council's power network [4],[5].

- GCC power network Steady-State Power Transfer Limit
- GCC power network Dynamic Voltage Limit
- GCC power network Transient Stability Limit
- GCC power network Power System Oscillation Damping Limit
- GCC power network Inadvertent Loop Flow Limit
- GCC power network Thermal Limit
- GCC power network Short-Circuit Current Limit

Herein, various studies indicate that each transmission system bottleneck and regional constraint may have one or more of the above mentioned characteristics.

1.2. Thesis Preface:

The principal aim of this research work is to investigate the power system network problems and to improve utilization of the existing power transmission system infrastructure on the GCC power grid through the application of advance power transmission control technologies. This research work also demonstrates comparative results with and without these devices on the GCC power grid. There are numerous existing problems which are persisting on the GCC power network. In order to understand and address GCC power network operational problems a long transmission model was developed and synthesized by incorporating its distributed control parameters. The power system has certain variables which are directly or indirectly impacted by the control. The voltage, angle and line impedance can be controlled by using conventional or advance power transmission technologies. The

GCC power grid's operational challenges, effectiveness of the shunt and series compensation, cost effective benefits and comparative analysis are also determined.

New control techniques are also introduced and investigated to control the FACTS devices more precisely at different locations on the GCC power network. A tailored PI controller configuration is implemented in order to utilize their operational capabilities based on predefined control limits which have been demonstrated in this research work. The STATCOM, SSSC and UPFC strategic reinforcement plan describes with facts and figures on a needs analysis basis. The Wideband Delphi technique is used to choose and select STATCOM, SSSC & UPFC devices for different locations based on their operations and control significance criteria on the GCC power grid. The STATCOM, SSSC & UPFC models' case studies results demonstrate their operational impacts on the entire GCC power grid at different locations on the GCC power grid.

These chapters validate the control and operational effectiveness of the STATCOM, SSSC & UPFC devices with and without being at their proposed locations. In these chapters dynamic responses of the STATCOM, SSSC, and UPFC devices operations also recorded. Effectively, the STATCOM, SSSC & UPFC controller's three control limits have developed and synthesized (+/-) minimum, (+/-), medium and (+/-) maximum compensation. The STATCOM, SSSC & UPFC, devices start and stop automatically by considering control combination blocks minimum medium and maximum inductive and capacitive modes of operations in parallel. These control limits are adjusted by configuring their corresponding PI control values by using Douglas J. Cooper PID control and optimization techniques which are then defined and discussed.

The simulation results indicate that these controllers oscillate between +/-2% minimum, +/-4% medium and +/-%6 maximum at both sides of transmission lines to adjust the reactive power compensation as required. These control boundaries will communicate to each other and adjust compensation based on sending and receiving end voltage deviation. These controllers have been configured in such ways to oscillate and inject or absorb controlled reactive power based on corresponding PI control values of each operating boundary.

The HVDC application and design criteria are also described on the GCC power grid. The detailed configuration of FACTS devices' integration (FACTS-FRAME) are formulated to obtain the desired results on the GCC power network. This chapter also demonstrates the dynamic capability to improve voltage profile, power angle and stability margin on the GCC power grid. After successful implementation, the GCC power network will entirely increase the power system loadability, reduce the losses and enhance sustainability of the power system performance as determined.

Finally, this thesis describes results and discussion in details. This comprises of PI controller selection process and significance, internal and external control significance, operational and maintenance control significance, STATCOM, SSSC, UPFC and HVDC devices operational and selection process significance.

1.3. Power system's current operations on the GCC power grid:

The GCC power system grid is configured and implemented into eight strategic power system operational directions in order to meet reliable and sustainable industrial and domestic customers' requirements at GCC Power network as shown in Figure 1-1 [3],[4]. Figure 1-2 indicates the GCC power network commissioning stages[5] and Figure 1-3 shows the power distribution on the GCC power grid.

i. The system was considered firstly, a double-circuit 400 kV, 50 Hz line stretching from Al Zour substation (Kuwait) to Ghunan substation into (Saudi Arabia) with an intermediate connection at Fadhili (Saudi Arabia) and its associated substations.
ii. Secondly, a back-to-back HVDC link introduced as a 380 kV interconnection, 60 Hz, system at Fadhili into Saudi Arabia in order to develop proper synchronization or communication with other GCC power systems, which are 50Hz frequency.
iii. Thirdly, a double circuit 400 kV overhead line stretching and partially connected with submarine link from Ghunan substation to Al Jasra substation in Bahrain along with its associated substations.
iv. Fourthly, a double circuit 400 kV line stretching from Ghunan substation to Salwa substation into Saudi Arabia along with its associated substations.
v. Fifthly, a double circuit 400 kV line stretching from Salwa substation to Doha South substation into Qatar and its associated substations.
vi. Sixthly, a double circuit 400 kV, 50 Hz line stretching from Salwa substation to Ghuwaifat substation in the United Arab Emirates along with its associated substations.
vii. Seventhly, a double and a single circuit 220 kV, 50Hz line stretching from Al Ouhah in the United Arab Emirates to Al Wasset substation in Oman along with its associated substations; finally, a centralized control room was established at Ghunan in Saudi Arabia in order to control power system operations within all GCC countries with a certain degree of precision at different voltage and shared power perspective.
viii. Furthermore, Figure 1-2 & 1-3 demonstrate the commission phases and power sharing at different locations on the GCC power network.

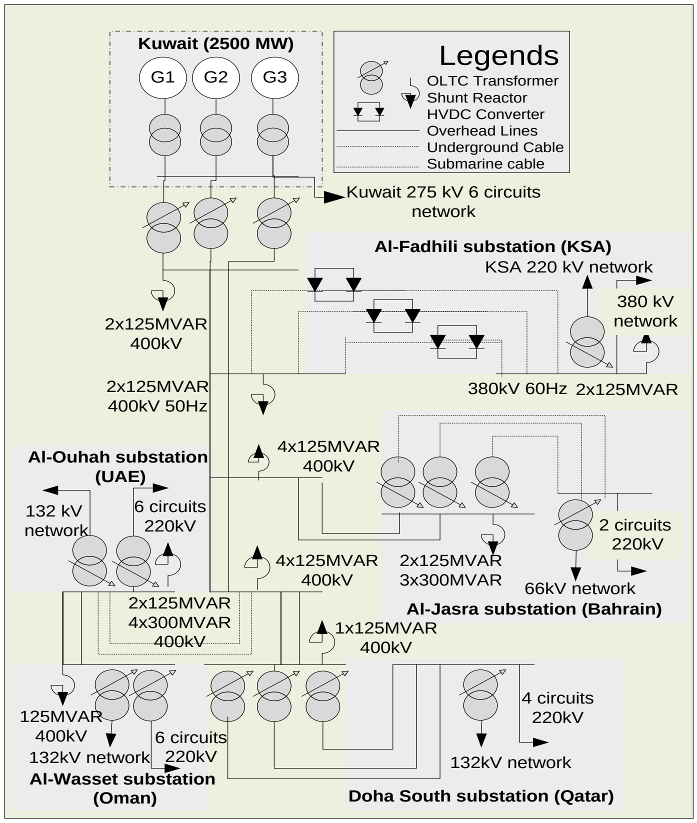


Figure 1-1: Single line diagram of GCC interconnection power grid[4]

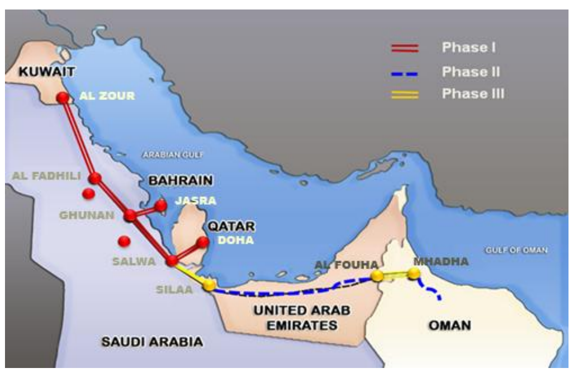


Figure 1-2: GCC power grid commissioning phases[5]

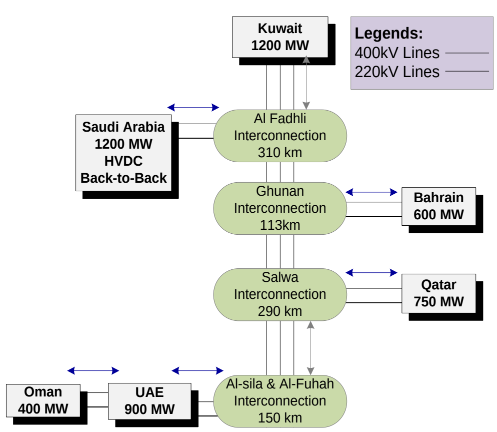


Figure 1-3: GCC Countries power sharing operations

1.4. Challenges on the GCC Power Grid:

It has been identified and determined through various operational scenarios as well as with in-house multiple studies that the GCC grid is encountering enormous underlying issues as listed below. The GCC grid is widely interconnected, involving connection inside the utilities own territories which extended to inter-utility interconnection then to inter-regional and international connection within the GCC grid. The GCC grid established due to economics and technical reasons, to reduce the cost of electricity as well as to improve the voltage quality, enhanced power flow control and power system reliability/availability and power sharing on a regional basis within the GCC power network.

a) Poor voltage quality on the GCC network:

Recently, studies have indicated that there is poor voltage quality at the receiving ends in Qatar, Oman and Kuwait. In order to support and maintain the voltage level without any (SAG/ Swell) conventional capacitors/reactors are provided at the receiving ends. These devices are taking a couple of cycles of 50 (60Hz) cycles and this is one and done or on/off operations.

b) Bottleneck in transmission and interconnected systems:

The AC systems are linked at various locations, power-flows can occur dependent on changing conditions in all six (GCC countries) networks as well as outages of any line. Whereas, when the power is transmitted into a meshed network, undesired power flows will load other parts of the network system, and this leads to bottlenecks in the network systems operations.

c) Poor load flow control on the GCC grid:

At present the GCC transmission facilities are confronting many limiting network parameters as well as an inability to direct power flow. In the AC Power network system, given the insignificant electrical storage, this reflects that the electrical power generation and load must balance at all times. If power generation is less than the load on the GCC grid, the voltage and frequency drop, and thereby the load goes down to equal the generation minus the transmission losses. If voltage is propped up with the reactive power injection then the load will go up, and frequency will keep dropping and the system will collapse. Alternative, if there is inadequate reactive power the system can have voltage collapse.

d) There is adequate power generation available on the GCC grid: the active power flows from the surplus generation areas to the deficit areas, and it flows to all parallel paths available which involve extra high voltage transmission lines.

e) **Limited power transfer capacity on the GCC grid**: The existing GCC AC network is serving with limited Power Transfer capacity to the neighboring countries. Firstly the long AC transmission lines have massive losse**s, secondly the inherently AC network cannot be overloaded.**

1.5. Why FACTS control devices needed on the GCC grid:

Through various practical application and research work, it has been indentified and determined that FACTS devices are offering a time-domain sustainable solution to overcome power transmission contingences: likewise on the GCC power grid with a degree of precision. FACTS controllers have an ability to control the interrelated parameters that govern the operations of power transmission systems which including series impedance, shunt impedance, current, voltage, phase angle and damping of oscillation at various frequencies below the rated frequency. The FACTS controllers can enable a power transmission line to run near its thermal capacity limit without endangering the power system operation, which may lead to transferring maximum power capacity near its thermal limit. The following FACTS controllers are strong candidates to be implemented to enhance power system operations on the GCC power grid [6], [7], [8].

1.5.1. STATCOM and SVC:

Static synchronous compensator and SVC controllers are giving a strong impact on voltage quality, but a medium impact on system stability and negligible impact on load flow control as demonstrated in Figure 1-4. The shunt controllers' encompassed variable impedance, variable source or a combination of these. Principally, the shunt controllers inject current into the system at the point of connection. Variable shunt impedance connected to the line voltage causes a variable current flow; hence the demonstrate injection of current into the line. As long as the shunt injected current in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Other phase relationship will involve handling real power as well [9], [10].

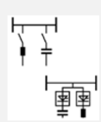
Principle of Operating parameters	Device	Scheme	Impact on GCC Power System Performance		
			Load Flow	Stability	Voltage Quality
Shunt compensation: To control the power transmission line voltage	MSCR: Mechanical Switched Capacitor/ Reactor)		X	X	X X
	SVC: Static Synchronous Compensator		X	X X	X X X
	STATCOM: Static Synchronous Compensator		X	X X	X X X
Influence Legends	X: Low or no	X : Small	X X : Medium		X X X: Strong

Figure 1-4: Voltage control shunt compensation

1.5.2. SSSC (Subsynchronous Series Controller):

The series compensator is reducing the line impedance in order to increases the system performance as demonstrated in Figure 1-5. The series controllers' encompassed variable impedance (capacitors and reactors), and power electronic based variable source of main frequency, sub synchronous and harmonics frequencies or a combination of these serve the purpose effectively. Principally, the series controllers inject voltage in a series into the system line at the point of connection. Variable shunt impedance connected to the line voltage causes a variable current flow; hence demonstrating injection of current into the line. As long as the series injected voltage in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power.

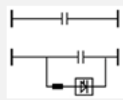
Principle of Operating parameters	Device	Scheme	Impact on GCC Power System Performance		
			Load Flow	Stability	Voltage Quality
Series Compensation: To Vary the power transmission line impedance	FSC: Fixed Series Compensation		X	X X X	X
	TPSC: Thryrister protected Series Compensation		X	X X X	X
	TCSC: Thyrister controlled Series Compensation		X X	X X X	X
Influence Legends	X: Low or no	X : Small	X X : Medium		X X X: Strong

Figure 1-5: variation of the line impedance by series compensation

1.5.2.1. SSSC Basic:

VSC (Voltage-Source-Converter), which is used for capacitive series compensation of the power transmission line, is called the Static Series compensator. The aim of capacitive series compensation is to considerably reduce the effective power transmission line impedance from sending to the receiving end. Multipulse, multilevel or PWM converter conventional VSC varies phase angle not voltage magnitude. No power source is on the dc bus, just energy stored in the capacitor. The slight change in voltage angle will allow a small amount of reactive power to flow to the DC bus in order to charge or discharge the capacitor bank.

1.5.2.2. Voltage Control through SSSC:

This is direct and fast control; the AC voltage magnitude can be varied by changing modulation ratio. Herein, there are a couple of pitfalls with considerable switching losses and turn-off time in devices. Hence by varying the “DC” link voltage to the center of the system for better response for required reactive power compensation.

1.5.2.3. SSSC Outer control:

The SSSC injects a series voltage into the transmission line system to improve voltage quality. The voltage injection is based on outer control parameters (reactance and current control).

1.5.3. Thyristor control series compensation (TCSC):

By adding the capacitive series compensation rapidly this then varies the power transmission line’s effective impedance in order to increase the power flow, improve the transient stability, power oscillation, and subsynchronous resonance (SSR) damping.

1.5.3.1. TCSC Basics:

Resonance imposes limits on the firing angle, it also improves boost C or L. and it will also reduce the impedance values. In fact, the voltage is distorted while TCR conducts (variable impedance model inaccuracy). Ratio of X_L/X_C impacts performance (impacts resonance and ratio from 0.1 to 0.3 is ideal) likewise current implementation of TCSC at Kayenta and Slatt.

1.5.3.2. TCSC Control Loops:

- Open loop: fixed firing angle control and reactance control.
- Closed loop current control model and reactance control.
- Overvoltage protection in **TCSC** controls (Inductor fully in the circuit (alpha=0) and TCSC looks inductive.

1.5.3.3. TCSC Reactance control mode of operations:

The TCSC reactance control maintains a fixed reactance through changes in the power system. The reactance command can be varied from a central operating point or from a further control loop, such as a damping control.

1.5.3.4. TCSC Current Control options:

- **Constant current control:** to keep current through the line constant through load variations within the controllable range of TCSC.
- **Secondly, current tracking control**: to keep the line current at a fixed ratio to the total load current (spread over several lines) within the controllable range TCSC.

1.5.3.5. TCSC External Control:

External control does not really vary with this type of series compensator, but the internal control is a bit more specific. A variable impedance type compensator is not always seen as voltage injections.

1.5.4. UPFC (Unified Power Flow Controller):

Figure 1-6 indicates that various investigation results validate that the UPFC controller has a strong impact to enhance Power transmission performance by address voltage quality, load flow control and power system stability in particular (dynamic stability, transient stability, steady state stability, voltage collapse, and frequency collapse) in order to meet growing Power delivery operations requirements.

This is combination of series and shunt compensation controllers, which are well controlled and coordinated the manners or the unified power flow controller with a series and shunt element in order to meet stringent operational requirements on the GCC power grid. Predominantly, the shunt compensation controllers will inject current into the system through the shunt part of the controller and the series compensation controller will inject voltage in series in the line through the series part of the controller. However, the shunt and series controllers are Unified Power Flow Controllers; there can be a real power exchange through the Power link.

1.5.5. HVDC (High Voltage Direct Current):

There is no reactive power flow on the DC line and there is no technical limit to the distance over which the power may be transmitted by cables or overhead transmission lines. The limit of the distance is economic, since the power losses in the transmission lines have become an unacceptable limit, when the practical conductor is used. Full and fast control of the Power flow, enhancement of the AC power network (AC Power oscillation damping capability, increased transmission capability in parallel line) is as demonstrated in Figure 1-6. Herein the HVDC line losses are smaller. It is possible to bring more power through the DC link without increasing fault level. No reactive compensation for DC a line is required [23].

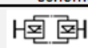
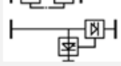
Principle of Operating parameters	Device	Scheme	Impact on GCC Power System Performance		
			Load Flow	Stability	Voltage Quality
Series and Shunt compensation: to control the load flow	HVDC (B2B, LDT)		X X X	X X X	X X
	UPFC: Unified power Flow Controller		X X X	X X X	X X X
Influence Legends	X: Low or no	X : Small	X X : Medium		X X X: Strong

Figure 1-6: Load flow control by series/shunt compensation

1.6. Aim and Objective:

To configure and implement HVDC/FACTS control devices on the GCC power grid at large by using PID (Proportional-Integral-Derivative) control and tuning parameters in order to optimize HVDC/FACTS devices operations and control with high degree of precision. Firstly, to develop an independent control model of each FACTS device (STATCOM, SSSC and UPFC) to determine their operational and control capability on the GCC power grid to address time-based power transmission system contingencies. In order to validate each model's results real-time operating data will be compiled and filtered prior to utilizing at the modeling and simulation stage of each FACTS device. These results will provide a multiple road map to accomplish the desired research work.

Secondly, to develop a multi variable controller that will be able to communicate and control STATCOM, SSSC & UPFC devices in an operation at times at different locations on the GCC power system grid. Develop an optimization technique to determine the composite location of the STATCOM, SSSC & UPFC devices and their operating parameters, which are delivering or absorbing reactive power compensation to enhance over-all power system network performance accompanying by reducing the network losses. Validation of this technique will be ascertained against the data obtained from the GCC water and power development authorities.

This optimization technique will also be extended to develop a Power network in the GCC countries through an optimization and integration process to enhance and stabilize network performance, and, in addition to that, to optimize and control the power system flow within two countries or more. Furthermore as a drawback standpoint of this study, the power exchange ought to be monitored and examined on a critical basis to take preventive measures for any possible network violation, which may lead to the potential GCC blackout.

1.6.1. Thesis Structure Outlines as Followed:

Chapter No 1 describes the summary of the proposed project on a needs analysis basis, vision and mission. Power system operational and control challenges are also explained on the GCC power network in order to address poor voltage quality (sags & swell), poor load flow control and limited power transfer capacity issues. It has been also illustrated why FACTS device are vital and viable to implement the GCC power grid by considering its operational benefits and criticalities.

Chapter No 2 describes four patterns of literature reviews to understand and realize current research accomplished in the area of FACTS/HVDC devices implementation. In this chapter it has been focused on STATCOM, SSSC, UPFC, HVDC controller tuning methodology by using optimum P-I-D tuning parameters. In this respect large numbers of research papers and articles are reviewed thoroughly to carry out detailed research more practically in order to understand the current research in these areas that have been accomplished. And to identify the areas where, more research is required.

Chapter No 3 describes the long transmission line model and its distributed control parameters, as well as the compensation factor at each section of the defined transmission line on the power grid network. This chapter demonstrates the shunt compensation of long transmission lines, simplified model and phasor diagram, ideal shunt compensation characteristic, ideal reactive power requirements, capacitive and inductive mode of operations through STATCOM**.** This chapter also describes the series compensation of long transmission line, simplified SSSC control model and its application with both capacitive and inductive mode of operations. Furthermore this also describes the HVDC operational challenges, cost effective benefits, and HVDC current applications in the world at large. In this chapter the HVDC application, deliverables and long-term benefits are discussed. Principally how the HVDC system can be implemented to address various power systems operational and control issues related on the GCC power system grid. In this chapter techno-economic analyses are demonstrated based on the current application of the FACTS/HVDC devices.

Chapter No 4 describes the PI, PD and PID controller application in order to control the STATCOM, SSSC and UPFC devices operations in multiple directions. In this chapter various PI control models have been developed and simulated to produce the desired results in order to meet operational requirements on the GCC power grid.

Chapter No 5 describes the application of STATCOM between Qatar and Bahrain on the GCC power grid. This chapter is divided into different sections to explain the STATCOM model case study in sequence. Firstly the GCC power system operational background and problems are discussed on the GCC power grid, STATCOM selection process, STATCOM case study and reinforcement plan. In the last section STATCOM model's dynamic performance and results are presented.

Chapter No 6 describes the application of the SSSC between the United Arab Emirates and Oman on the GCC grid. This chapter is divided into different sections to explain in sequence, firstly the GCC power system operational background and problems, SSSC device selection process, SSSC case study and the reinforcement plan are discussed. In the last section SSSC model's dynamic response and results are demonstrated.

Chapter No.7 describes the application of the UPFC between the KSA and Kuwait on the GCC grid. This chapter is divided into different sections to explain in sequence, firstly the GCC power system operational background; UPFC reinforcement plan, UPFC device selection process, and UPFC case study are discussed. In the last section UPFC model's dynamic response and results are demonstrated.

Chapter No.8 describes the application of HVDC on the GCC grid, design criteria, design study reviews, HVDC system description, rectifiers operations, inverters operations are discussed. In the second section of this chapter, the HVDC schematic, HVDC system analysis, power delivery model of long transmission line, intertie link results are demonstrated.

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Chapter No.9 describes the implementation of tailored-made various FACTS devices by using the new technique "FACTS-FRAME" which indicates robust integration control topology. In this chapter also identified and determined are the existing intertie link and its viabilities on the GCC countries power network. This chapter also demonstrates how the STATCOM, SSSC and UPFC devices are communicating to each other in order to share reactive power compensation requirements at different locations in the GCC countries. Each device adjusts the (+/-) capacitive and inductive compensation factor based on provided sixth control limits. These control limits are operating by its corresponding PI control values. This chapter also describes that the FACTS-FRAME has a great potential to run all three FACTS device in parallel jointly (centralized control) or independently (de-centralized control) as per power system operational requirements.

Chapter No.10 demonstrates the significance of this research work in different perspectives. These significances are categorized in order: firstly, discussed PI controller configuration parameters selection process, secondly, internal and external control parameters, thirdly, operations and routine maintenance, fourthly devices selection process, and lastly devices control and operations significances.

Lastly, this work is concluded by presenting the development of five layers of inter-related FACTS-FRAME architecture. The FACTS-FRAME demonstrates the centralized and decentralized control system to integrate all three devices at different locations on the GCC power grid. It also illustrates the major potential economical benefits as well as the technical impact to improve power transmission network performance by implementing the centralized and decentralized control system operations on the GCC power grid.

1.7. Summary:

This chapter describes the vision and mission of FACTS devices application in the GCC Power grid, and how various FACTS devices can be implemented. There has also been indentified and determined the successful application of proposed devices by learning from the various referred materials published. Hence, this chapter framework aims to analyze and design various options of FACTS devices as well as implementation in a specific domain on the GCC Countries in order to address all sorts of current or underlying Power system issues with a degree of precision.

This chapter also presents electrical power system challenges in the GCC countries at large. Herewith, a large amount of control and operating data has been collected and compiled, reviewed and understood, which is related to current application of FACTS devices in the world at large.

CHAPTER 2

Literature Review

2.1. Introduction:

This chapter describes the current research carried out to implement FACTS/HVDC device(s) to improve electrical power systems control and operations on the GCC power grid. In this chapter numerous investigations have been discussed and demonstrated with facts and figures. The STATCOM, SSSC, UPFC, HVDC and PID's different control approaches have been introduced and demonstrated by the various researchers. Based on their investigation various simulations results indicate a capability and capability of these different research approaches and their current applications to improve power system control and operations. It also focused on different time-based control and operational situations and their implementation in order to get maximum benefits out of these approaches. In this chapter each FACTS device individual control and operations are also discussed.

Herein, various approaches and concepts are studied to implement appropriate FACTS/HVDC devices. These devices are offering rigorous solutions to address various power system stalemates. Based on these studies different control and operational scenarios have been explored for successful implementation. FACTS control experts determined that the FACTS devices have the capability and capacity to provide dynamic well-controlled reactive power compensation with a degree of precision. This will improve receiving and sending ends' voltage quality, power angle and stability margin.

Research into HVDC/FACTS devices design, production, configuration and implementation cover a vast range of topics and a diversity of FACTS control designing perspectives. From the accompanying literature, it is always a clear what is design and control context in for the research topic. Many researchers make a significant contribution in HVDC/FACTS control designing and their implementation in the world at large. This is always appropriate as there are several clearly distinguishable works completed in the FACTS/HVDC devices control and operations areas. Hingorani, Narain G [1] is careful to classify research findings into six broad categories of FACTS devices design, production and implementation: voltage source converters, self and line commuted current sourced converters, static shunt compensators (SVC, STATCOM), static series compensators (GCSC, TSSC, TCSC), static voltage phase angle regulator (TCVR, TCPR), combined compensator (UPFC, IPFC).

2.2 Scope of the literature review:

The literature encompassed material that pertains to the business of HVDC/FACTS control devices design, production and implementation in the commercial world. Diverse sources have been utilized in this research but the coverage of this review has been designed to provide insight in HVDC/FACTS control devices design production, configuration and implementation specifically.

2.2.1 STATCOM application:

Metin D., and Ali Ozturk [35] studied to identify and determine the optimal point for the STATCOM compensator for static voltage stability. IEEE-14 buses system was utilized for analysis and simulation purposes. The results indicate that the static voltage instability can be improved drastically without and constraints. S. Zheng, and S. Fang [37] demonstrated the application of three-phase VSI-based distributed STATCOM. The results indicate that control strategy is very promising and providing required static compensation performance as well as tremendous dynamic response. Rajive, and Vinay [36], introduced and illustrated the utilization of a PV solar plant as STATCOM in order to manage reactive power compensation based on load variation. This is very much evident that the PV solar system has the potential to be utilized as a STATCOM device. S.Teleke, B.Gudimetla [38], demonstrated the application of STATCOM to address power quality issues at a refinery which consists of large numbers of induction motors. The results indicate promising improvement in power system operations as well as witnessed economic benefits. A. Nazarloo, S. H. Hosseini, E. Babaei [25], introduced and demonstrated a new control technique of STATCOM control and operations. The prime aim of this research work is to mitigate the power system quality issues and improve distribution system performance under all types of fault conditions line to line, fault double to ground fault.

T. Fuji, K. Tema [40] demonstrated the application of 450MVA STATCOM to improve voltage profile and stability of the power system network. It also diminished the over-voltage effect due to the Ferranti phenomenon and outage fault at heavy load conditions. Juan C, Johan David Elizondo Nagy [33], demonstrated the application of STATCOM and Battery Energy storage System and their benefits to improve the power system network operations. The results indicate that the power system still survives under the severe contingency conditions. H. M. Pirouz, M. T. Bina [31], introduced new control topology to compensate and control unbalanced and nonlinear medium voltage presence of load and source harmonics at the power system network. At the same time the DC capacitor voltage was also controlled more precisely. M. Bhaskar, S.S.Dash, & C.Subramani [34], introduced and demonstrated a STATCOM controller to help in balancing the dynamic load of the power system network. As a control strategy, if line current is less than presumed the STATCOM will generate the compensating current which will be taken by the load without any constraints. G. ZHAO, J. LIU[29], introduced and integrated phase and amplitude control into STATCOM control strategies. And detailed analysis indicates very promising results to improve the STATCOM and system performance.

Ibrahim B., and Sad El-Marcy[28], introduced detailed model of the STATCOM consist of two six-pulse converters by using ATP draw analysis software. Based on this technique each part of STATCOM can be determined. Chunyan, Zhenjiang[27] introduced new technique of online monitoring and fault diagnostic system in order to settling the decision problems of system reliability, safety and maintenance..

D. Innuzzi and Lauria[32], introduced and demonstrated the voltage source inverter (STATCOM) and its integrated variable load. They focused on dynamic performance and stability margin of the system at different control strategies. Shu-Jen Steven [39], investigated reactive power compensation mode of operations and operating strategies in order to improve voltage quality by utilizing STATCOM device..

G. Reed and J. Paserba[26], investigated and explained the STATCOM model rated ±100 MVA at 138 kV, which offers power system operations and control with a high degree of reliability that is obtained by using new design configuration of modular converter. This system also comprises cooling system, step-up transformer, filter banks and switchgear in order to secure power system operations and control (SDG & E Taleg, ±100 MVA). G. Reed and J. Paserba, explained STATCOM rated ±43MVA at 115 kV, control model's application and its long-term benefits. It also indicates that STATCOM has capacity and capability to provide dynamic compensation of power system network.

2.2.2 Application of SSSC control device:

M. Faridi & H. Maeiiat [45] investigated the active and reactive power as well as the damping power system oscillation in the transient mode. The results indicate the effectiveness of the SSSC in controlling power flow and achieved the desired value of reactive and active power as well as damping oscillation. A.D. Falehi and A. Doroudi [41] introduced and investigated a complementary damping controller for the SSSC (Static Synchronous Series Compensator) to improve the power system stability. Genetic Algorithm optimization technique was also investigated and produced very promising results which support the study. Cao Taibin & Qian Bifu [43], investigated the constant voltage control of SSSC and also determined its characteristics. Herein a multi-order nonlinear system is used to design the controller. Finally, the results prove that the control strategy is very much viable and robust. Xiang Zheng, and Chao Wang [53], investigated subsybchrnous resonance (SSR) in the series compensated power system. The proposed control strategy of the SSSC active damping control will mitigate the SSR component. The adopted technique has very vigilant future in the power system. S. Khani, M. Sadeghi, S.H. Hosseini[52], investigated the selection process of the SSSC by using genetic Algorithms. The prime contribution of the SSSC is for damping control in order to improvement power system dynamic response and its stability. Based on these configurations the desired results were obtained.

G. Abdollahi Sarvi & M. Tavakoli Bina [44], investigated the application of SSSC to determine its switching functions and with small changes in these functions at different states of SSSC simulations. The results indicate some improvement in the transient and steady states of the power system operations. M. Sedighizadeh , M.Toulabi[47], demonstrated the application of SSSC to provide an additional damping in the power system. During any disturbance in the power system the machine in that system will oscillate and clear the disturbance and the transient energy becomes zero. This will settle at a stable operations point. R.K Pandy and NK Singh [49] demonstrated a new design technique of SSSC damping controller with a level of relative stability. The results indicate the effectiveness of the new control model.

S. Jamali, A. Kazemi [50], [51] demonstrated the effects of inter phase, phase to phase and three-fault during SSSC device operations and investigated the impact of SSSC. The results indicate the effectiveness of SSSC during fault conditions by varying the line impedance. M. Khederzadeh, and A. Salemnia [46], investigated the application of a distance relay for the protection of the transmission line in the presence of SSSC. The results indicate improvement of distance relay protection system performance at different fault conditions. Ali Ajami and mehdi, [42] investigated controlling the injected voltage in order to control the required reactive power compensation. For the injected voltage a separate DC current control is applied which produced a fast dynamic response and a high quality of current and voltage waveforms. Paivel Zunfiiga and Juan Ramirez [48], investigated to identify SSSC operations based on 46-pulse VSC (voltage source converter). They have presented a detailed analysis of 48-pulse VSC configuration and its operations without any ambiguity. Based on SSSC voltage with reference to the current flow through as well as the DC capacitor charge and discharge the procedure was also explained in their research work. Xiao. P. Zhang [53] investigated the SSSC control device multi-functional control for power flow analysis. This can be formulated for steady state control based on the following reasons (to control active and reactive power, voltage at the bus, impedance reactance) this research investigation indicates very good results. Javier Chivite-Zabalzaand Miguel Rodríguez[56], investigated SSSC (Static Synchronous Series Compensator) power electronic based device that has the capability and the capacity to control power flow through a power transmission network. The primary aim of this research work is to enlarge the stability region of the conventional power system network. The research indicates very promising results informing of a power system improvement with an enhanced stability area. M. R. Banaei[57] described the SSSC voltage source converter connected (coupled) with a transformer to provide series compensation to the transmission line. As per research it indicates that the power flow in the line decreases when the injected voltage in the line emulates an inductive reactance. Alternatively, the power flow increases when the injected voltage emulates capacitive reactance in series in the transmission line. Hernandez, P. Eguia, [54], describes the composite approach to identify and determine the series line compensation by using SSSC. In order to meet the required compensation synchronous voltage source can be used to provide controllable series compensation. It also investigated the idea/concept that the external DC power supply can provide another source of compensation if there is voltage drop across the resistive component of the line impedance. S. Adeghzadeh & M. Ehsan investigated that application of FACTS devices to increase power transmission system loadability. This may be constrained by a transient stability limit. The model results show that by using the proposed method to increase power transfer in the network this then leads to an improved transient stability limit. This research was carried out at the Sharif University of Technology in Iran.

2.2.3 Application of UPFC control device:

Suppakarn Chansareewittaya and Peerapol Jirapong [67] introduced and demonstrated TSSA (Tabu Search and Simulated Annealing) with search space-managing methods to determine the optimal location of UPFC device for implementation in order to enhance power transfer capacity form the transmission line. Ch. Chengaiah R. V. s. Satyanarayanl [58] introduced how UPFC controller's can raise the stability limit of the power transmission system. They have also witnessed single and double transmission line systems performance by implementing UPFC device. S. L. Silva Lima & E. H. Watanabe [66] introduced and demonstrated new and simple structure to control the transmission line voltage precisely. The UPFC configuration allows for controlling the line voltage at given point of the circuit very easy without any constraints. Juan Li & Kun Wang [63] introduced and demonstrated a nodal power injection model of the UPFC control device for three phase power flow calculation. They have used decoupling compensation theory to measure three phases power flow. The model simulation indicates very promising results. Rajive Tiwari, K.R.Niazi, *&* Vikas [65] Gupta introduced and illustrated a novel model control approach for enhancing voltage stability margin of the power system. This is an innovative approach where real power exchange of the shunt and series compensators is decoupled with each other. Jia-jun LIU & Ying QI [61] introduced and demonstrated a new scheme of the power transmission which can integrate the function of the power system synchronization and the UPFC. The model simulation indicates desired results. Chia Chu & Hung Chi [49] introduced and illustrated energy functionality of the UPFC control model for improving transient stability of network preserving power systems. The UPFC control model simulation indicates very promising results. Mojtaba Khederzadeh [64] demonstrated the UPFC controller's operating characteristics on the power transmission line and positive impact of distance protective relays. He also focused on the series injected voltage magnitude and phase angle on the performance of protective relays at different fault conditions. D. W. Lee and S. I. Moon [60] introduced and demonstrated coordinated control algorithm of the UPFC control device. The primary aim of this algorithm is to stringent control the voltage level to avoid any inverter capacity limit problem. The simulation process indicates the desired results.

Yixin Ni & Zhenyu Huang, investigated UPFC with power frequency model with its dc link. In this study shunt and series components are also discussed. The UPFC control strategies have a very strong impact on power transmission network performance. The simulation test results indicate that the UPFC device has a strong impact to control constant power flow through power transmission network. In addition to that constant series compensation is very useful for first swing stability as well as for providing additional control, which is very effective in damping inter-area power oscillation. Li LI, Zongxiang LU, Arui [69], investigated a UPFC control device integrates properties in order to meet shunt and series compensation of power transmission network. These properties can be altered in order to increase power transfer capability and stability. This research indicates that by implementing new control strategies there is significant improvement in power transfer capability and stability. Kazemi, S. Jamali, H. Shateri [68], investigated that the Unified Power Flow Controller (UPFC) has capability to control the line impedance, phase angle and reactive power in the power system transmission network. The UPFC simulation results indicate improved power system stability by providing proper operations block. Effectively, improper UPFC operations can deteriorate the power system stability.

Kazemi, S. Jamali, [68] also investigated the UPFC effects to increase power transfer capacity through the power system network. In fact, UPFC has capacity and capability to control three parameters of power system operations independently. The simulation results indicate reasonable power transfer through the network after adjusting and optimizing its defined control parameters. M. Boyra∗ and J.-L. Thomas[70], investigated the UPFC performance during the network fault condition. Primary aim of this research is to observe the UPFC behavior and its capability to compensate the transmission line in order to secure reactive power and active power flow and diminish the fall-off of the bus voltage if there is ground fault. However, the simulation results indicate very promising response of UPFC under typical fault condition. M. Kenan [72] investigates the UPFC reactive power and voltage balance in the power transmission network. In order to determine these issues two control schemes have discussed one conventional and other nonconventional. In the first scheme the shunt converter control the UPFC voltage and DC link voltage along with series converter controls the transmission line reactive and real power. In the non-conventional scheme the shunt converter provides reactive power and maintains the DC bus voltage and the series converter controls the real power and the UPFC bus voltage. The results indicate that conventional control gives good performance and unconventional control topology will enhance UPFC operations performance.

2.2.4. Application of HVDC power transmission system

Yong Li & Zhiwen Zhang, [80] introduced and demonstrated new HVDC transmission system to deliver bulk power. They have also introduced new converters transformers as well as inductive filters. Simulation results indicate that the HVDC technology is very effective and efficient. Qing Zhong, Yao

Zhang & Lingxue Lin [76] introduced and illustrated a study on HVDC Light for its enhancement of AC/DC hybrid transmission system and multi-infeed HVDC system. Simulation results indicate that the HVDC light is more effective and efficient compared to conventional HVDC. D.T. Oyedokun & K. A Folly [74] introduced and illustrate the new configuration of HVDC and hybrid HVAC and HVDC power transmission line and the effect of DC faults on the transient stability of a Multi-Machine Power System with a two transmission line.

Chunyi Guo, and Chengyong Zhao [73] introduced and demonstrated a double-infeed HVDC (high Voltage Direct Current) power system, combining a conventional HVDC transmission and voltage-source converter based VSC-HVDC technology. Simulation results indicate that DI-HVDC technology has a great potential compared to a conventional HVDC system. Yan Liu, Zhe Chen [78] introduced and illustrated a general model of dual in-feed HVDC system by applying Voltage Source Converter - HVDC, which can be used as an element in large multi in-feed HVDC system. The simulation results indicate that the double in-feed HVDC system has better control compared to a single in-feed HVDC system.

Yong Li, & Zhiwen Zhang [78] introduced and demonstrated new circuit topology of the traditional current source converter based on the HVDC transmission system, along with a new inductive filtering method. Simulation results indicate that this topology maintains the stable operating performance and represents the good fault-recovery ability when suffering the typical faults. Y.P. Li, D.G. Wang, A. P. Hu [77] introduced and illustrated an HVDC control and protection real-time simulation system based on a SIMADYN platform in line with practical HVDC projects. Simulation study results indicate that the RTDS tool is very viable to measure and design control and protection system. Hongtao Wang & Chengming [75] introduced and illustrated a HVDC power system restoration procedural approach to enhance power system controllability, stability and reliability. The simulation results indicate that the HVDC system has a great effect on power system operations.

2.2.5 Application of PID controller tuning:

Chiha, J. Ghabi and N. Liouane [89] investigated and demonstrated new technique tuning of PID controller by using Multi objective Differential Evolution. Simulation results indicate that a new tuning method has a better control system performance compared with the conventional approach. Yingjian Xu, & Wei Zhang introduced and illustrated a first order plus dead time (FOPDT) control parameters technique. By using this method desired results were achieved. The simulation results indicate its simplicity and accuracy. ZOU Dexuan & GAO Liqun introduced and demonstrated a new technique of PID controller optimization robustness by using MGHS (modified global harmony search algorithm). Therefore, experiments' results indicate that MGHS has a great potential to improve PID controller optimization process.

Maryam Khoie & Karim Salahshoor [94] investigated and demonstrated a Genetic-AIS (artificial Immune System) algorithm for PID controller tuning by using a multi-objective optimization framework. Simulation results indicate the robustness of the PID controller response without any constraints. Yanzhu Zhang & Jingjiao Li [95] introduced and illustrated a Genetic Algorithm to design of fractional order of PID controller to enahnce PID controller response and accuracy. Simulation results indicate robustness of the PID controller. Jyh-Cheng & Sheng-Wen Lin [93] introduced and demonstrated a design concept of PID controller for a process based on inverse response and time delay. Whereas, the analytical tuning rule for PID control parameters is developed and synthesized. Simulation results indicate the superiority of the proposed design technique.

B.Nagaraj & N.Murugananth[87] investigated and demonstrated a soft computing technique to enahnce the PID controller response and robustness with a degree of precision. Simulation results indicate that the using of a soft computing technique for the PID controller improves the performance of the process on time-base without any limitations. Bin Zuo & Jing Li [88] introduced and demonstrated discrete-time extremum seeking algorithm based on annealing recurrent neural network(EAA-ARNN) for PID controller's auto tuning purposes. Firstly, there was introduced the integral squared error (ISE) and secondly, the discrete-time ESA-ARNN. Simulation results indicate that ESA-ARNN have a performance to enahnce PID controller robustness. Jie Li & Jingkuan Gong [91] introduced and demonstrated a Genetic Algorithm and PSO (particle swarm optimization) to enahnce PID controller capability with a degree of precision. In addition, PFO (particle filter Optimization) was also introduced to achieve a better performance while reducing the computation complexity. Simulation results indicate the effectiveness of the proposed algorithm.

2.3. HVDC Projects:

2.3.1 World first HVDC link in Australia

- Direct Link rated capacity 180MW/65km underground cable, from Queensland to New South Wales, in 2000.
- "Murray Link rated capacity of 200MW/180KM underground cable, from south Australia to New South Wales, in 2002.
- Basslink rated capacity 480MW/360km underground, undersea and overhead line, from Tasmania Island to Victoria.

2.3.2. First Merchant HVDC link in US:

- Cross sound project rated capacity of 330MW/40Km sea cable, from Connecticut to Long island.
- Lake Erie project rated capacity 990MW/145km from Ontario IMO to PJM.
- Harbor Cable project rated capacity 660MW/40KM, from PJM to new jersey ISO.
- Multi terminal 3- Bipoles link rated capacity 9000MW, from Illinois to California.

2.3.3. Trans Canada HVDC links in Canada:

- The HVDC link 2000MW/ 1600KM, from Low cost generation in oil sands region to north Alberta [165-169].
- **Brian Gemmell (IEEE PES Dallas 2003)** described that the HVAC with FACTS devices Series and shunt compensation. These devices are operating in two modes of control operations fixed and variable control mode. The variable control mode will provide précis slow and fast switching operations either stepped or continuous variation.

2.4. FACTS projects:

Phase shifting transformer (Quad Booster) is implemented with rating 2950MVA, 400kV in order to inject quadrature voltage in series and phase varied by Tapchanger. Thyristor controlled Series Capacitor (TCSC) implemented 202Mvar, 500kV at Slatt/BPA and 108Mar, 500kV Imperatriz and Serra da Mesa/Electobras. Static Var Compensator is shunt connected, which encompassed a/the? Thyristor controlled reactor (TCR), Thyristor Switched capacitor (TSC), and Fixed Capacitor (FC). STATCOM based on IGBT and GTO in order to meet continuous variable compensation +/- 75 Mvar (0-225 Mvar Installation Range) response time <100ms and >98% availability. Following projects are in operations without any constraints. The first high-power STATCOM in the United States was commissioned in late 1995 at the sullian substation of the Tennesse Valley Authority (TVA) for transmission line compensation (Nominal capacity +/- 100 Mvar Short term capacity +/- 120 Mvar, Transmission line voltage 161kV and converter output voltage 5.1kV, GTO rating 4.5 4KA(peak). The first Unified Power Flow controller in the world, with totaling rating of +/- 300 MVA, was commissioned in mid-1998 at the Inez Station of the American Electric Power (AEP) in Kentucky for voltage support and power flow control.

The first lesson was learnt from the materials that the reshaping of energy deregulation of the electricity market, the conventional concepts and practices of electrical power systems operations and management has been changed. These are leading to a power system stalemate (deadlock) in demand versus supply as well as constraint on quality issues. To resolve these issues an introduction of flexible AC transmission system (FACTS) technology came into existence in the digital era.

The second lesson was learnt from the review materials that the FACTS devices are contributing dynamically to control the power flow in the network, which reduces the flow in heavily loaded lines and also provides an instrumental approach for increasing and shifting the loadability of the network along with low system losses, improved stability of network and reduced cost of power production in multi aspects. The third lesson was learnt from the materials, it is important to identify and determine the optimum location of STATCOM, SSSC and UPFC devices because of their considerable implementation costs. Henceforth, an optimal location of FACTS devices and multiple controls have also been determined with and without considering the investment cost of FACTS devices and their impact on the generation, transmission and distribution systems. This is very important to build-up an effective algorithm to identify and assess the optimal location of FACTS devices and their controls based on the economic saving (reduction of FACTS devices installation) and their impact on existing system operational stability as well as reduction in energy losses. In various papers it has also addressed the importance of the different types of FACTS devices and implementation at different locations of the power system to get maximum benefits out of these.

2.5. Summary

The following are the main standpoints the previous work did not investigate fully or partially and this work will be addressed. The primary contribution of this research work is to investigate the STATCOM, SSSC and UPFC devices impact on the GCC power grid. This research work also demonstrates comparative results with and without these devices on the GCC power grid

a. Firstly it describes the research study benefits, the GCC power grid background and the STATCOM, SSSC and UPFC strategic reinforcement plan.
b. Secondly it describes the significance of the STATCOM, SSSC & UPFC selection process and each device-weighted score by using the Wideband Delphi technique.
c. Thirdly it demonstrates the STATCOM, SSSC & UPFC models case studies results and its operational impacts at all sides on the GCC power grid by using PI new configuration control parameters. This section also indicates the effectiveness with and without the STATCOM, SSSC & UPFC at their proposed locations and also shows the dynamic response of the STATCOM, SSSC, UPFC operations.
d. Fourthly it also discusses selection process results, controller significance and the STATCOM, SSSC & UPFC impact in detail on the GCC power grid.
e. Based on the above-mentioned literature reviewed, the PID controller was configured to meet power system operational requirements on the GCC power grid.

CHAPTER 3

Power Transmission Lines Modeling & Series/Shunt Compensation

3.1. Introduction

In this chapter a power transmission line model was developed in order to identify and determine various important operating and control parameters. These are very viable in order to tailor different FACT/HVDC devices as appropriate to serve the purpose, which will be implemented at various locations on the GCC power grid**.** This chapter discusses long transmission lines' basic principal, operating parameters and compensation levels and how these could be obtained by putting its operational and security criticalities into consideration. Hereby, a simple shunt and series compensation technique was adopted to develop STATCOM and SSSC models to implement in order to provide appropriate shunt and series compensation in the GCC power grid as applicable. This chapter also describes UPFC control and operational parameters, which is providing an adequate compensation to the power long transmission lines by putting its operational and security criticalities into consideration. Hereby a simple Unified Power Flow Control compensation technique was adopted to develop a UPFC control model and to implement it in order to provide an appropriate shunt and series compensation by using Unified Power Flow Controller on the GCC Power grid as applicable.

Furthermore, this chapter illustrates the viabilities of HVDC transmission system for bulk power transfer and HVDC link and their applications in the GCC Power grid if applied. Herein HVDC operations and characteristics are also described.

3.2. Long transmission lines model:

The power transmission line comprises of three distributed parameters, inductance, capacitance and resistance. Each section of the transmission line has its own inductance, capacitance and resistance. These parameters are very important and complicated from a calculation standpoint to develop an accurate mathematical model. But the accuracy is very important to analyze long transmission line's transient and high frequency effects. In order to establish main principles of the power transmission line by using good approximated models which are easy to setup or deal with. In this study, there will be a determination of the physical dimensions of the power transmission line by assessing inductance and capacitance values. These derived values will be used to establish a simple model to describe the long transmission line operations.

These models are based on "π" and "T" network approximation which are justified line lengths of up to 250 kilometers. Herein, the transmission lines more than 250 kilometers and for a more accurate solution following distributed parameters per unit values are considered to develop a model**.**

And ABCD generalized circuit constant parameters as shown below in Figure 3-1. These parameters can be expressed in the series impedance (z) per unit length and shunt admittance (y) per phase, as denoted in equation (3.1) and (3.2) [11].

$$z = r + j\omega L \qquad (3.1)$$

$$y = g + j\omega C \qquad (3.2)$$

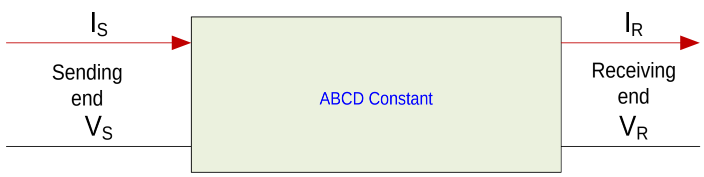


Figure 3-1: Transmission line model [12]

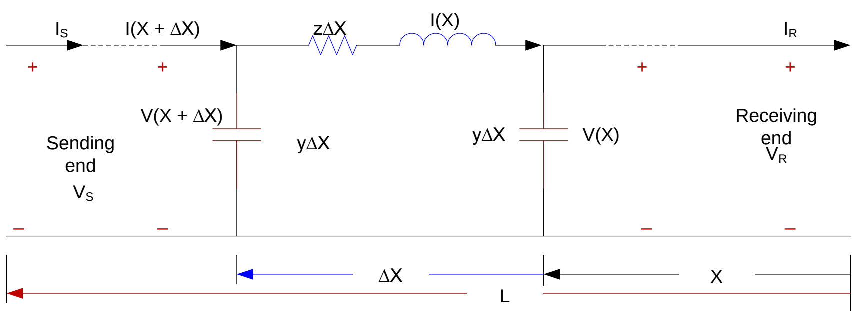


Figure 3-2: long lines with distributed parameters [12]

Figure 3-2 shows the long lines with distributed parameters, which are used to calculate the required compensation. In long transmission lines this is mandatory to define γ, which known as the propagation constant and characteristic impedance is denoted by Z_C as given in equation (3.3) and 3.4) [11].

$$\gamma = \sqrt{zy} = \sqrt{(r + j\omega L)(g + j\omega C)} \qquad (3.3)$$

$$Z_c = \sqrt{\frac{Z}{y}} = \sqrt{\frac{(r+j\omega L)}{(g+j\omega C)}} \qquad (3.4)$$

And the ABCD constant parameters of uncompensated transmission line are denoted in equation (3.5), (3.6) and (3.7).

$$A = D = \cosh(\gamma\ell) \quad (3.5)$$

$$A = Z_c \sinh(\gamma\ell) \quad (3.6)$$

$$C = \sqrt{\frac{\sinh(\gamma\ell)}{Z_c}} \quad (3.7)$$

Henceforth, by controlling shunt and series compensation, a significant improvement in the power transfer within acceptable voltage limit can be achieved. Consequently, the formulated sequence can be used to examine the A and B parameters of a compensated transmission line as denoted in equation (3.8) and (3.9).

$$A = 1 + \left(\frac{YZ}{2}\right) + \left(\frac{Y^2Z^2}{24}\right) + \left(\frac{Y^3Z^3}{720}\right) \quad (3.8)$$

$$B = Z\left[1 + \left(\frac{YZ}{6}\right) + \left(\frac{Y^2Z^2}{120}\right) + \left(\frac{Y^3Z^3}{5040}\right)\right] \quad (3.9)$$

Where:

Z= total series impedance of the transmission line

Y= Total shunt admittance of the line

3.3. Long transmission line's compensation

To compensate for long transmission lines, it is essential to divide the line into various sections by using compensation at each section. This controls the voltage profile and facilitates switching and reduces short circuit currents. Typical 500kV, 1000km scheme may be used a compensation totaling of 1200Mvar. Hence this is desirable to implement shunt and series compensation at intermediate points as well as at the ends of the lines.

3.4. shunt compensation of the power transmission system:

The study indicates an increase in line length results in an increase in shunt capacitance. Therefore, this is very important to provide some external devices or control methodology to inform of shunt compensation to reduce this parameter. The line charging current becomes quite significant when the line is slightly loaded, it means when there is a sudden loss of load. Effectively, there is excessive capacitive power (generation of leading VAR) that causes the voltage to rise at different points along with the transmission line. This is obviously an undesired operating condition. Based on these consensuses this problem is overcome by using shunt compensation. In practice, due to economic reasons and other potential control issues the shunt compensation device can offer 70% compensation maximum e.g. $h_1 = Y_{L1}/Y_{C1}$

Where YL1 is the total admittance of the two combined shunt reactors, therefore, 70% compensation is adequate to maintain the line charging current at an acceptable limit. If the line shunt capacitance of a 400 km line is $5x10^{-6}$ F. the compensation provided 70% equal to h1 = 0.7 calculate the inductance L_1 inductance of shunt reactor at each line end and he system frequency is 50 Hz [10], [11].

$$Y_{L1} = Y_{c1}.h_1 \qquad (3.10)$$

$$Y_{c1} = 2.\pi.f.C_{c1} \qquad (3.11)$$

Y_{C1} = line admittance, C_{C1} = shunt capacitance and Y_{L1} = Total admittance

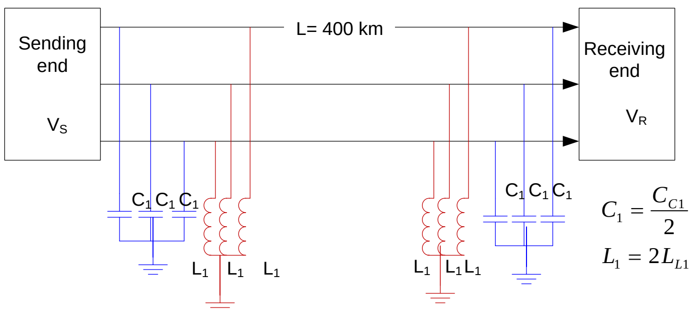


Figure 3-3: long transmission line shunt compensated [10]

Furthermore, Figure 3-3 indicates the simplified model of a power transmission system. Two power grids are connected by a transmission line which is assumed to be lossless and represented by X_L. $V_1\angle\delta_1$ and $V_2\angle\delta_2$ symbolize the voltage phasors of two grid buses with angle $\delta=\delta_1-\delta_2$ between the two. The corresponding phasor diagram is shown in Figure 3-5 (b) [11], [12].

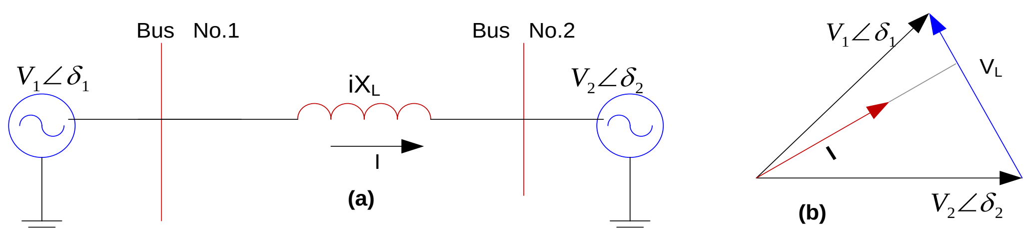


Figure 3-4: Power transmission system: (a) simplified model (b) phasor diagram and the magnitude of the current in the transmission is denoted in equation (3.10): [15]

$$I = \frac{V_L}{X_L} = \frac{|V_1\angle\delta_1 - V_2\angle\delta_2|}{X_L} \quad (3.12)$$

The active and reactive components of the current flow at Bus No. 1 as denoted in equation (3.13)

$$I_{d1} = \frac{V_2 sin\delta}{X_L}, \qquad I_{q1} = \frac{V_1 - V_2 cos\delta}{X_L} \quad (3.13)$$

The active and reactive power at Bus No. 1 as denoted in equation (3.14)

$$P_1 = \frac{V_1 V_2 sin\delta}{X_L}, \qquad Q_1 = \frac{V_1(V_1 - V_2 cos\delta)}{X_L} \quad (3.14)$$

Similarly, the active and reactive components of the current flow at Bus No. 2 as denoted in equation (3.15).

$$I_{d2} = \frac{V_2 sin\delta}{X_L}, \qquad I_{q2} = \frac{V_2 - V_1 cos\delta}{X_L} \quad (3.15)$$

The active and reactive power at Bus No. 2 as denoted in equation in (3.16).

$$P_2 = \frac{V_1 V_2 sin\delta}{X_L}, \qquad Q_2 = \frac{V_2(V_2 - V_1 cos\delta)}{X_L} \quad (3.16)$$

Equation (3.14) indicates the active and reactive power/currents which can be regulated by controlling voltage, phase angle and line impedance of the transmission line. As Figure 3-4 indicates, the active power will reach the maximum when the phase angle at $\delta = 90$ degree. Practically, a small angle is used to keep the system stable from the transient and dynamic oscillation. Generally, the compensation is divided into shunt and series mode of operations as per power system smooth operations without any constraint.

3.4.1 Shunt compensation:

A device that is connected in parallel with a transmission line is called a shunt compensator. It is referred to as a compensator since it compensates for the reactive power in the ac power system to.

a) Improve the voltage profile

b) Improve the power-angle characteristics

c) Improve the stability margin

d) Provide damping to power oscillations

Figure 3-5 indicates the ideal shunt compensator as an ideal current source that supplies only reactive power and no real power. It is connected at the midpoint of a lossless line to support the voltage [12].

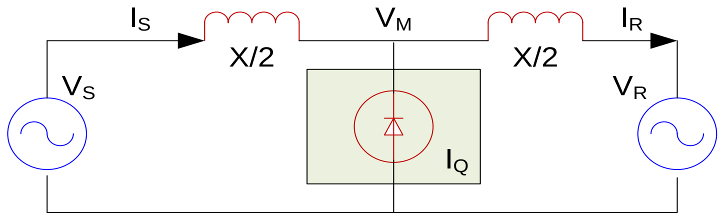


Figure 3-5: Ideal shunt compensator:[12]

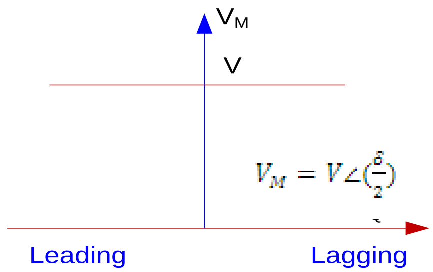


Figure 3-6: Ideal shunt compensator characteristics [12]

Figure 3-6 shows the ideal voltage-current characteristics of an ideal shunt compensator in which the midpoint voltage is held constant irrespective of the current injected. It will hold constant voltage irrespective of current injected or draw I_Q is lagging/leading does not matter. The injected current must have phase Quadrature with the midpoint voltage to meet the proper compensation requirements. As a result the real power injected by the compensator will be zero.

$$Vs = V\angle\delta \qquad V_R = V \qquad V_M = V\angle(\frac{\delta}{2}) \tag{3.17}$$

Equation (3.16) indicates V_S sending-end voltage, V_R receiving end voltage and V_M Midpoint voltage, which are denoted in Figure 3-7.

$$I_s = \frac{V\angle - V\angle(\delta/_2)}{jX/2} \qquad I_R = \frac{V\angle(\delta/_2) - V}{jX/2} \tag{3.18}$$

I_R current received at the receiving-end and I_S indicates the current injected by the source, which are expressed in Figure 5-5

$$I_Q = I_R - I_S \qquad I_Q = -J\frac{4V}{X}\left\{\left(1 - cos\left(\frac{\delta}{2}\right)\right)\right\}\angle(\frac{\delta}{2}) \tag{3.19}$$

Equation (3.17) indicates I_Q current that is injected into transmission line by the compensator at mid point as indicated in Figure 3-6.

3.4.2 Real and reactive power:

Midpoint shunt compensation improves the power flow over a line. The real power flowing through and the reactive power absorbed by the line refer to Equation (4.9). The reactive power generated by the shunt compensator under defined boundaries to meet operational requirements refers to Equation (3.20).

$$P_E = \frac{2V^2}{X} sin\left(\frac{\delta}{2}\right) \quad Q_Q = \frac{4V^2}{X}\left[1 - cos\left(\frac{\delta}{2}\right)\right] \quad Q_L = \frac{8V^2}{X}\left[1 - cos\left(\frac{\delta}{2}\right)\right] \tag{3.20}$$

P_E indicates the power transfer over the transmission line and Q_Q reactive power generated by the shunt compensator. Herein the Q_L indicates the reactive power absorbed by the transmission. Figure 3-7 indicates that this is assumed V^2/X = 1.0 pu, for a real power transfer of 1.0 per unit, a reactive power injection of roughly 0.5359 per unit will be required from the shunt compensator. However for 2.0 per unit real power, 4.0 pu reactive power is needed as given below [12], [15].

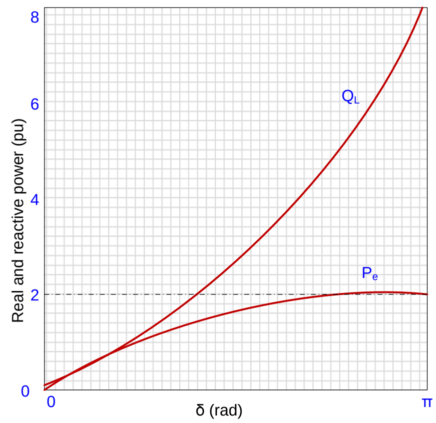


Figure 3-7: Q_L reactive power absorbs by the transmission line against the real power (P_E)[12]

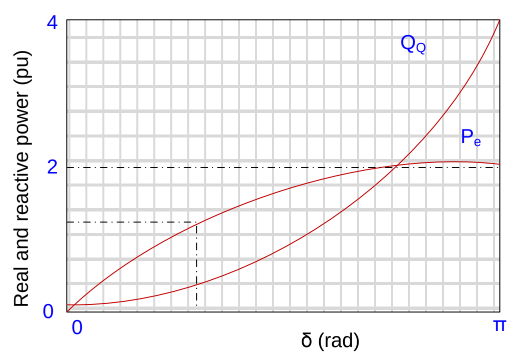


Figure 3-8: Q_Q reactive power generated by the shunt compensator against the real power (P_E)[12]

Figure 3-7 and 3-8 indicates how much reactive power is required to transfer 1.0 real power, similarly to transfer 2.0pu real power how much reactive power is required. The reactive power injection can be lowered by lowering the midpoint voltage; as shown in Figure 3-9.

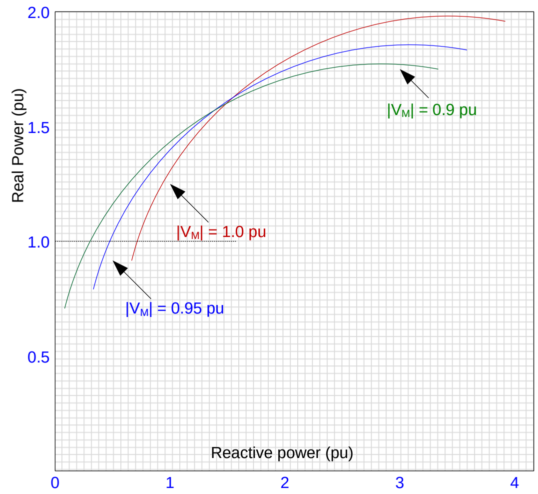


Figure 3-9: reactive power requirements [12]

Figure 3-10 indicates the stability improvement during power generation. The A1 shaded area indicates the acceleration and A2 the de-acceleration during power generation based on Pm(mechanical Power). In the second portion A3 indicates the acceleration area and A4 indicates the small de-acceleration area based on Pm (mechanical Power), which is providing a large margin because sufficient reactive power is being injected by the shunt compensator, and it is transferring more real power without endangering the power system stability[19], [20].

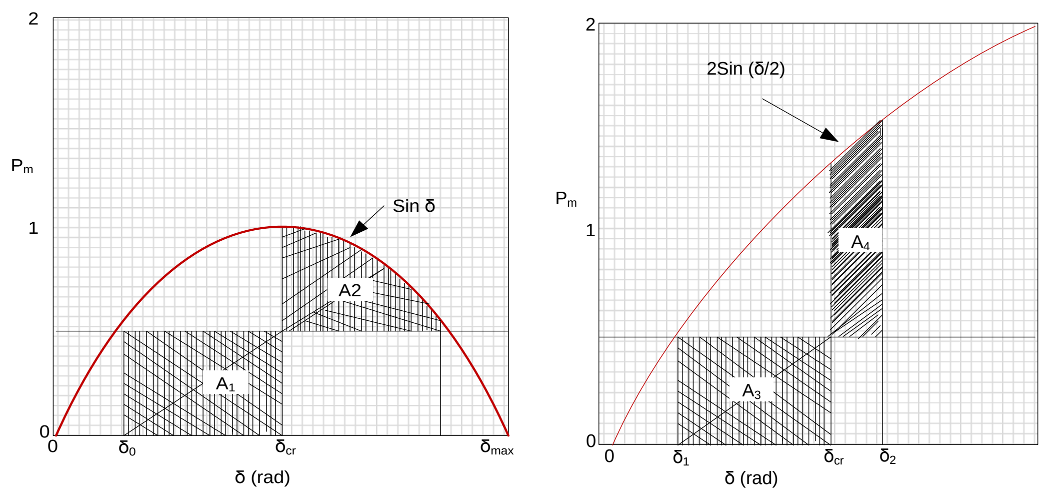


Figure 3-10**:** stability improvement based on equal criteria methodology [12]

3.4.3 Power swing damping:

P_M is the mechanical power input. However the electrical power *Pe* is defined as a function of the load angle and the magnitude of the voltage at the midpoint. These are the integrated factors which can alter the power transmitted over a transmission line for constant voltage at the two ends.

3.4.4 VI curves & relationship:

Figure 3-11 indicates the midpoint voltage increases linearly with capacitive load current and decreases with inductive load current. Midpoint voltage decreases linearly with inductive load current and will also lag with voltage. Midpoint voltage increases linearly with capacitive load current and it will also lead with voltage.

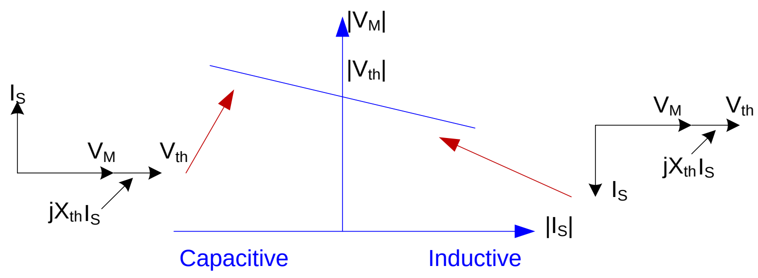


Figure 3-11: VI curves and relationship [12]

3.4.5 Shunt reactive compensation:

Shunt reactor with their compensating effect on the capacitive generation of the line offer an economical and technically sound means of controlling the undesired over voltage. In this chapter the main focus is on over-voltage under steady state conditions and the effect of the shunt reactor on such over-voltages.

3.4.6 Degree of shunt compensation level: (K_d)

In many investigations determining the maximum Power transfer, the amount of shunt reactor required on the transmission line is defined as the degree of shunt compensation (K_d).

$$K_d = \frac{B}{Im\{y\}\ell} \qquad (3.21)$$

K_d is defined the total inductive susceptance of shunt compensation, “B” total charging susceptance of line $Im\{y\}\ell$

3.4.7. Effect of resistance of the line on power frequency over-voltage under no load conditions:

Figure 3-12 indicates a simplified single-phase representation of a three-phase transmission line. The voltage profile along the line is symmetrical about the center point of line. The condition for the voltage at any point M to be maximum is δ=0 and $\ell_1 = 1/2$, which clearly indicates that voltage on the line is maximum at the mid-point of the line. Therefore the effect of resistance of the line on power frequency over-voltage under no load condition is negligible. This is illustrated in Figure 3-13 which confirms the curves plotted from the mid-point voltage for different line length for actual and lossless line and it is clear that voltage at mid-point of the line for an actual and lossless is the same, no matter where the point of maximum voltage (with reactor) is located. The reactor mounted in the middle (point of maximum voltage without reactor) of the line requires minimum reactor rating to bring the maximum voltage on the line within limit. Without over-stressing the existing insulation of the line, the maximum permissible value of the voltage at any point of line should not exceed 1.05 times the rated nominal voltage. The condition of maximum voltage, anywhere on the line determines the required rating of the shunt reactor. When the reactor (Ypu) is mounted at the middle of the line the point of middle voltage is no longer in the center of line as shown in the Figure 3-14 [21], [22].

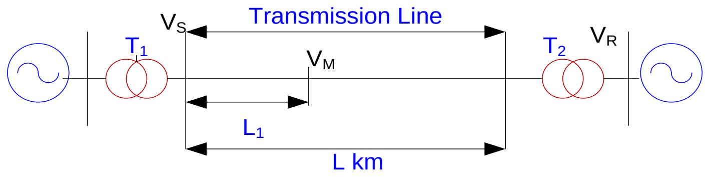


Figure 3-12: simplified single-phase transmission line[15]

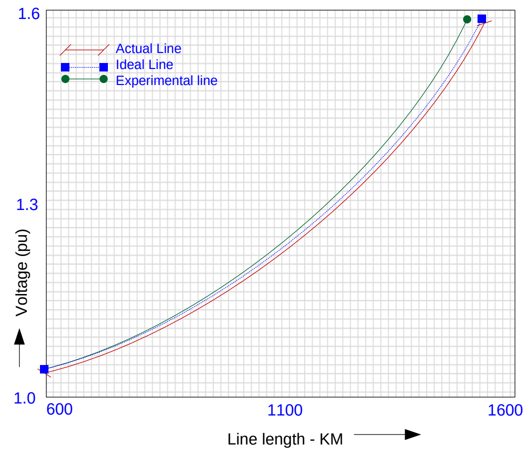


Figure 3-13: simplified single-phase line [15]

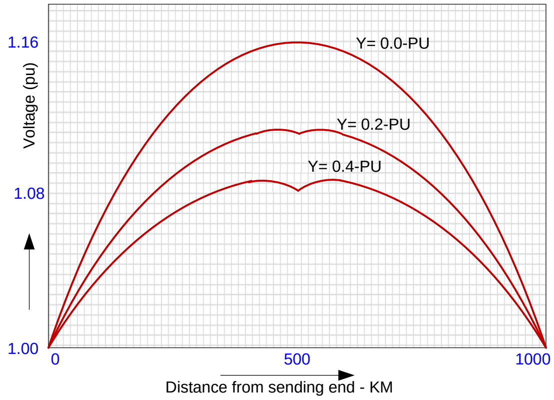


Figure 3-14: Voltage profile along 1000km line [15]

3.4.8. Shunt capacitive compensation:

In order to eliminate the phenomenon of SSR, in the connection, the utilities have considered the use of capacitive compensation as an alternative means of increasing transmission capacity. The prime benefit claimed by the shunt capacitance compensation is that it is possible to maintain nodal voltage at a nominal value through the injection of reactive power along the line. Another benefit is its capability to extend the steady state stability and improve damping when in conjunction with static VAR Controller. V_R and send V_S reactive Power P_R, and real Power Q_R at the receiving end of the line, the required capacitive M_{VAR} at the receiving end for a specified load can be easily computed. The Q value of the capacitor can be obtained as defined in equation (3.22).

$$M_{var} = \frac{V^2}{X_2} \qquad (3.22)$$

$$X_c = \frac{1}{\omega C} \qquad (3.23)$$

Figure 3-15 shows the simplified model of a power transmission system with shunt compensation. The voltages at two buses are assumed equal as V, and the phasor angle between them is δ. The transmission line is assumed lossless and represented by the reactance X_L. At the mid-point of the transmission line, a controlled capacitor C is shunt connected. The voltage magnitude at the connection point is maintained as V.

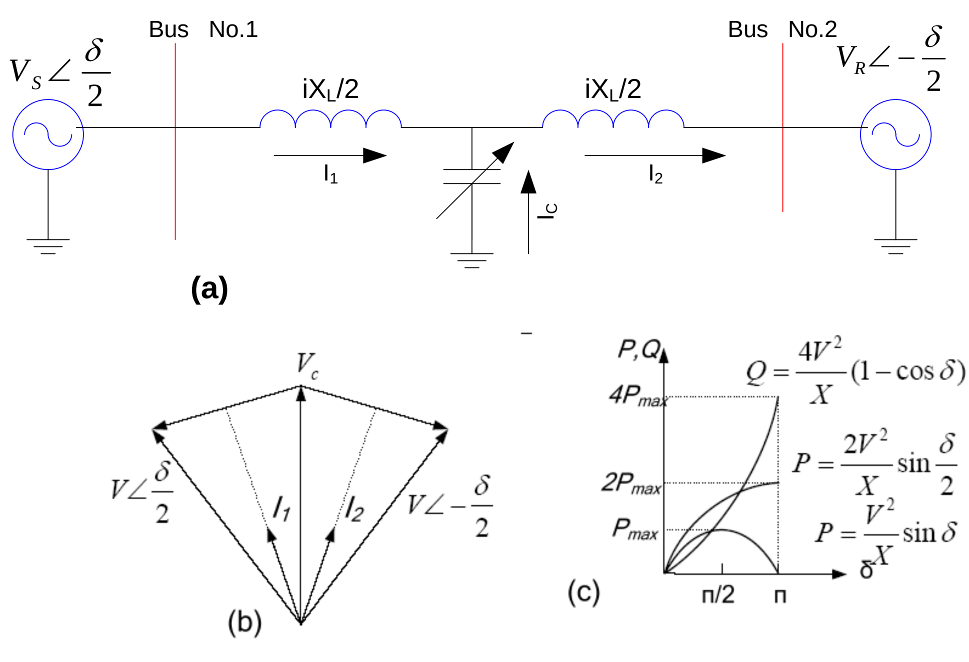


Figure 3-15: Transmission system with shunt compensation: (a) simplified model (b) phasor diagram (c) Power angle curve [15]

The active powers at bus 1 and 2 are equal as indicated in equation (3.24)

$$P_1 = P_2 = 2\frac{V^2}{X_L}sin\frac{\delta}{2} \qquad (3.24)$$

The reactive power injected (Q_C) denoted in equation (3.25)

$$Q_c = 4\frac{V^2}{X_L}\left(1 - cos\frac{\delta}{2}\right) \tag{3.25}$$

The transmitted power can be significantly increased, and the peak point shifts from $\delta = 90\ to\ \delta = 180$. The operation margin and the system stability are increased by shunt compensation. The reactive power compensation at the end of redial line is especially effective in enhancing voltage stability [23], [24].

3.4.9. STATCOM Operations:

1. A STATCOM consists of a SVS that is supplied by a dc storage capacitor C_{dc} as demonstrated in Figure3-16.
2. The SVS is connected in shunt with the ac system bus through a coupling transformer with a leakage reactance of X_T.
3. If ∠ θ=∠ φ, then the direction of the flow of purely reactive current Iq will depend on the voltage magnitudes V1 and V2.
4. If V1 > V2 then the current flows from the ac system to the SVS and the converter absorbs reactive (inductive) power.
5. If V2 > V1 then the current flows from SVS to the ac system and the converter generates reactive (capacitive) power for the ac system.
6. However pure reactive injection or absorption is neither possible nor desirable.
7. Since the converter is supplied by a dc capacitor, the voltage across the capacitor will fall if the STATCOM is not lossless.
8. The dc capacitor voltage can be regulated by replenishing the losses due to switching and in the coupling transformer circuit by drawing power from the ac system.
9. Therefore ∠ φ must lag ∠ θ by a small amount such that the dc capacitor voltage is held constant.
10. In a multi-step converter, the fundamental component of the output voltage is determined by the magnitude of the dc capacitor voltage.
11. Therefore the voltage magnitude V_2 can be increased or decreased vice-versa the magnitude of V_1 by charging or discharging the dc capacitor through the control of φ. This makes the control loop slow.
12. Pulse width modulation (PWM) can effectively be used in a multilevel converter. This has a better control response.
13. In a sinusoidal PWM, the fundamental component of the output voltage magnitude can be changed by changing either the capacitor voltage or the modulation index.
14. The capacitor voltage imbalance problem in diode-clamped topology makes its use restrictive. Alternatively flying capacitor topology can be used.

3.4.10. STATCOM benefits

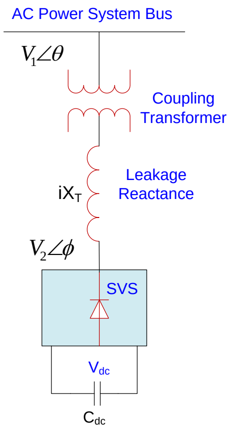
STATCOM	**Benefits**
	**1.** SVS (synchronous voltage source)
	2. Maximum compensating current is independent of system voltage
	3. Low losses at zero output
	4. Losses increase smoothly with both capacitive and inductive outputs
	5. Maximum delay in negligible
	6. No harmonic filtering required

Figure 3-16: STATCOM operational schematic [12]

3.5. Series compensation of the power transmission system:

As discussed earlier, the line shunt capacitance goes up if there is an increase in power transmission line length. Similarly, the series inductance also increased proportionally which will limit/decrease the power transfer capacity, steady state and transient stability margin and the system voltage will also drop excessively. These issues can be addressed by increasing the power system voltage, one more circuit in parallel and series compensation to reduce the series inductance of the long transmission line. There are two methods that are very much viable to achieve the maximum power transfer limit of the line. The first method is to increase the transmission line voltage. However, this will lead to an accumulating effect of cost increases in the generators. This is very expensive. The second method is by reducing the characteristic of line impedance. The reduction of the characteristic impedance of the line can be achieved either by changing the line dimensions or by adding series capacitors with the line. The line dimensions cannot be changed widely and it only creates a small impact characteristic impedance of the line. Therefore, the addition of capacitors in series with the line, also known as series compensation, is the best available method to reduce the characteristic impedance. The series compensation aims to directly control the overall series impedance of transmission line. The AC power transmission is primarily limited due to series reactive impedance of the transmission line. A series connected can add a voltage in opposition to the transmission line voltage drop, therefore reducing the series line impedance [23], [24].

Figure 3-17 shows the simplified model of a power transmission system with series compensation. The voltages at two buses are assumed equal as V, and phasor angle between them is δ. The transmission line is assumed lossless and represented by the reactance X_L. A controlled capacitor is series connected in the transmission line with voltage addition.

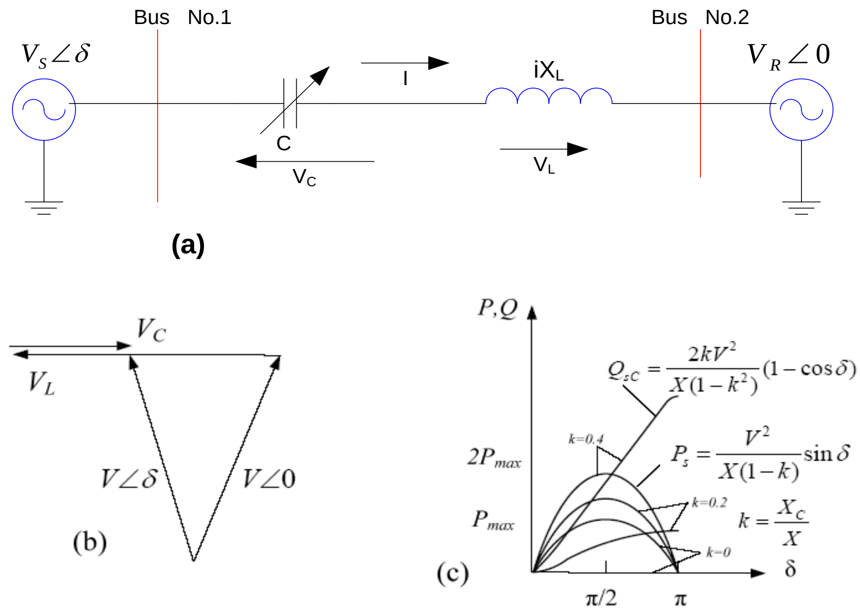


Figure 3-17: Transmission system with series compensation: (a) simplified model (b) phasor diagram (c) Power angle curve [12]

Equation (3.26) is defining the capacitance of C as a portion of line impedance:

$$X_C = kX_L \qquad (3.26)$$

Equation (3.27) is defining the overall series inductance of the transmission line.

$$X = X_L - X_C = (1-k)X_L \qquad (3.27)$$

Equation (3.28) is defining the active power transmitted through the power transmission line

$$P = \frac{V^2}{(1-k)X_L} sin\delta \qquad (3.28)$$

Equation (3.28) is defining the reactive power supplied to the power transmission line:

$$Q_C = 2\frac{V^2}{K_L}\frac{K}{(1-K)^2}(1-cos\delta) \qquad (3.29)$$

Figure 3-17 shows the power angle curve from which it can be seen that the transmitted active power increases with K factor.

3.5.1. Series capacitive compensation:

Series capacitors, which are connected in series with the line, are used to reduce the series reactance between the sending and receiving-ends. Series compensation can be provided a lumped or distributed. Figure no. 3-18 indicates a transmission line is divided into 10 sections and an equal π model represents of each section. A lumped compensation can be placed any location of the transmission line, and distributed compensation consists of splitting the compensation from a range of locations from 1 to 10. In comparison, between two types of series compensation, a lumped compensation gives better results than a distributed compensation from the point of view obtaining the maximum power transfer [35], [36], [37].

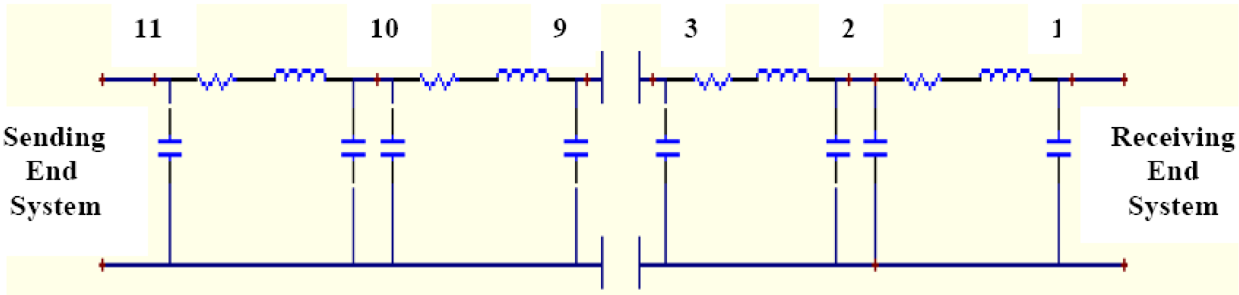


Figure 3-18: Transmission line compensated [15]

3.5.2. Degree of series compensation:

The percentage or degree of series compensation is used to analyze the transmission line with the required addition of series capacitors. It is defined as the fraction of capacitive reactance X_C and inductive reactance of the line as computed in equation (3.29)

$$K_s = \frac{X_c}{X_l} \qquad (3.30)$$

Since the objective is to identify and examine the amount of series capacitor on the line, therefore, it will be useful to define the degree of compensation as required in the total line impedance, which is computed in equation (3.30):

$$Z = R + j[X_l(1 - K_s)] \qquad (3.31)$$

3.5.3. Series Compensation Drawback:

One major drawback of series capacitor compensation is that special proactive devices are required to protect the capacitor or bypass the high current produced when a short circuit occurs. Also, the inclusion of series capacitor establishes a reasonant circuit that can oscillate the frequency below the normal synchronous frequency when stimulated by disturbance. This phenomenon is referred to as a subsynchronous resonance (SSR). A device which is connected in series with the transmission line or system is called a series compensator. Herewith, we will analyze how series compensator effects the system parameters as listed below.

a) Voltage profile-

b) System power angle characteristics-

c) Stability margin-

d) and damping of power oscillations-

The ideal series compensator is used to provide reactive power not real power as demonstrated in Figure 3-19. The installation of series compensator is not very much crucial it can be placed anywhere in the transmission line.

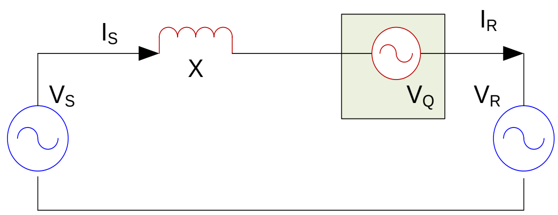


Figure 3-19: Ideal Series compensator [12]

3.5.4. Voltage profile series compensator at undefined location:

The series voltage must be injected in such way that the series compensator does not absorb any real power in the steady state operation as defined in equation (3.32).

$$V_Q = \lambda I_s e^{\pm 90^0} \qquad (3.32)$$

a) Where λ is a proportionality constant

The compensation ratio is $\lambda/_x$ is called the compensator level. If the compensator level is 50% than the $= {}^x/_2$. Lambda is also called the line impedance as given in the equation (3.32). Equation (3.33), (3.34) and (3.35) indicate the sending and receiving ends voltage as well as sending current [23], [24].

$$V_s = V\angle\delta \qquad (3.33)$$

$$V_R = V\angle 0 \qquad (3.34)$$

$$I_s = \frac{V_s - V_R - V_Q}{jX} = \frac{V\angle\delta - V}{j(X \mp \lambda)} \qquad (3.35)$$

3.5.5. Series compensator mode of operations:

Equation (3.35) expressed the pure capacitive mode of operation of compensator device. This is also called the capacitive mode of operations:

$$V_{Q=\lambda I_s e^{-90^0}} \rightarrow I_s = \frac{V\angle\delta - V}{j\,(X-\lambda)} \qquad (3.36)$$

Equation no.3.36 expressed the pure inductor mode of operation of compensator device. This is called the inductive mode of operations:

$$V_{Q=\lambda I_s e^{+90^0}} \rightarrow I_s = \frac{V\angle\delta - V}{j\,(X+\lambda)} \qquad (3.37)$$

3.5.6. Power angle control by series compensation:

The real and reactive powers at the sending and receiving ends as well as the required reactive power are calculated as formulated below.

a) Complex power:

$$P_s + jQ_s = \frac{V^2 sin\delta}{X \pm \lambda} + j\frac{V^2(1-cos\delta)}{X \pm \lambda} \quad (3.38)$$

b) Real Power:

$$P_R + jQ_R = \frac{V^2 sin\delta}{X \pm \lambda} + j\frac{V^2(cos\delta-1)}{X \pm \lambda} \quad (3.39)$$

c) Real Power flow over the transmission line:

$$P_e = P_s = P_R = \frac{V^2 sin\delta}{X \pm \lambda} \quad (3.40)$$

d) By reducing the Lambda (0.1,0.2,0.3….0.9) values curve will increase as per given equation:

$$V_{Q=\lambda I_s e^{-90^0} \to I_s = \frac{V\angle\delta - V}{j\,(X-\lambda)}} \quad (3.41)$$

e) By increasing the Lambda (0.1,0.2,0.3….0.9) values curve will reduce as per given equation:

$$V_{Q=\lambda I_s e^{+90^0} \to I_s = \frac{V\angle\delta - V}{j\,(X+\lambda)}} \quad (3.42)$$

If lambda is equal to reactance than there is no power flow in the line and line impedance will reach infinity. The real power will reverse if the load angle <30° degree. Only a small amount of power will transfer in a capacitive mode of operation. But the power will reverse at the inductive mode of operation. Figure 3-20 indicates two modes of series compensator operations; capacitive and inductive respectively. By changing the lambda values the series compensation can be shifted into capacitive or inductive mode operations [43].

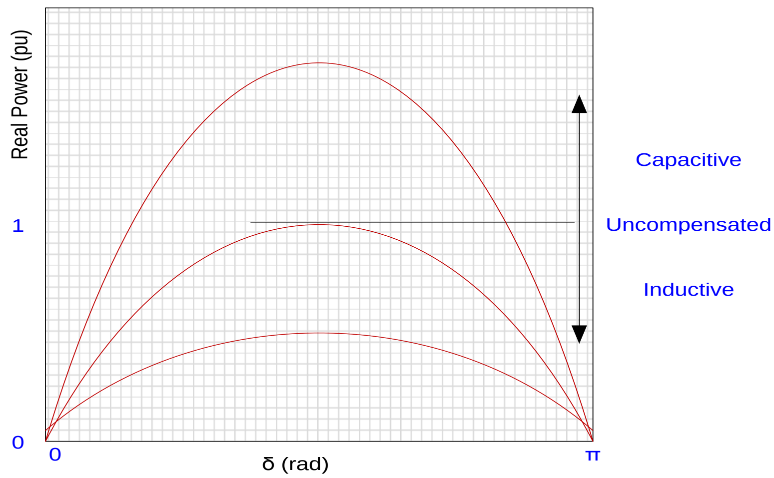


Figure 3-20: indicates the capaitive and inductive mode of operations [12]

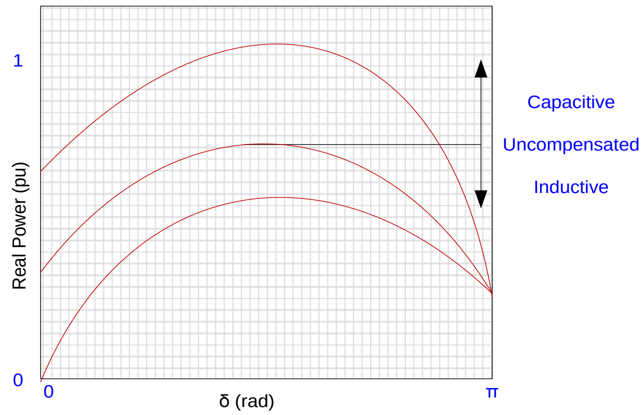


Figure 3-21: real power 0.5pu at 0 load angle [12]

Figure no. 3-21 indicates the real power 0.5 pu at 0 load angle. The real power will reverse if the load angle <30° degree. Only a small amount of power will transfer in a capacitive mode of operation. The power will reverse at inductive mode of operation.

3.5.7. Reactive Power Compensation:

The compensation level is normally denoted by (λ/X) in % values. Therefore to increase the real power transfer with respective reactive power requirement over the transmission line can be achieved by increasing compensation level. Figure 3-22 indicates at 60% compensation the real power 2.6 pu and reactive power requirements is 7.6 pu. And at 10% compensation the real power 1.1 pu and reactive power requirements is 0.2 pu.

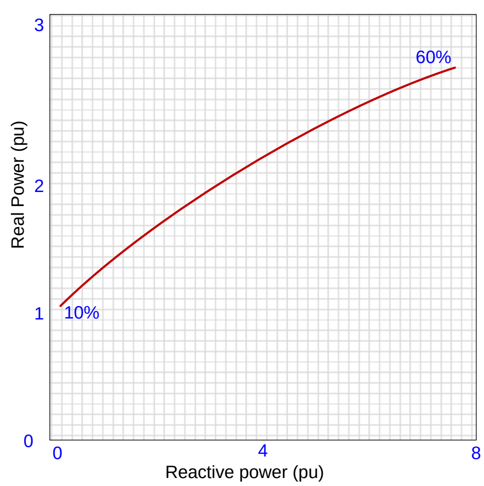


Figure 3-22: reactive power compensation [12]

3.5.8. Alternate source of voltage injection:

The series compensator injects voltage that is Quadrature of the line current. The injected voltage magnitude will be proportional to the magnitude of the line current. The injected voltage magnitude with equation given:

$$V_{Q=\frac{I_S}{|I_S|}e^{\pm 90^0}} \quad , \quad Q_Q = Im\left(V_Q {I_S}^*\right) = \frac{2\lambda V^2}{(X-\lambda)^2}(cos\delta - 1) \qquad (3.43)$$

Figure 3-23 indicates the capacitive mode of operations, where the V_Q will lag I_S at 90° degree (1.571 rad)

$$X|I_s| = |V_Q| + 2V\sin\left({}^{\delta}/_{2}\right) \tag{3.44}$$

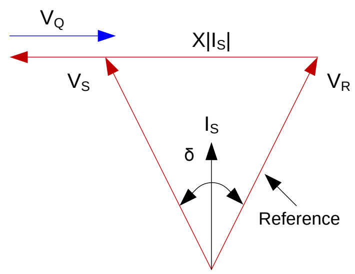


Figure 3-23: shunt compemnsator capactive mode of operations [12]

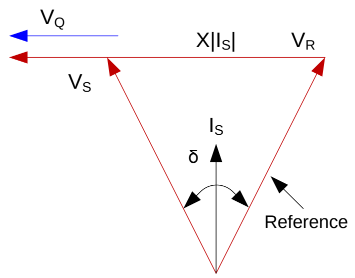


Figure 3-24: shunt compemnsator inductive mode of operations [12]

Figure 3-24 indicates the inductive mode of operation where the V_Q will lead I_S at 90° degree (1.571 rad)

$$X|I_s| = -|V_Q| + 2V\sin\left({}^{\delta}/_{2}\right) \tag{3.45}$$

The total power flow through the Power system as denoted in equation (3.45)

$$P_e = \frac{V^2}{X} sin\delta \pm \frac{V}{X}|V_Q| \cos(\delta) \tag{3.46}$$

3.5.9. <u>SSSC Operations</u>

SSSC also includes SVS synchronous voltage sources and coupling transformer that are connected in series with the line. The SSSC is operated in such a way that the injected voltage is almost in phase quadrature with the line current, its control schematic demonstrated in Figure 3-25. In the equivalent circuit of an SSSC compensated system, the SSSC is represented by a voltages source and impedance *(L_r,R_r)*. The SSSC is connected between buses 1 and 2 as demonstrated in Figure 3-27. The pair (L_1,R) represent the line and L_2 represents a transformer [23].

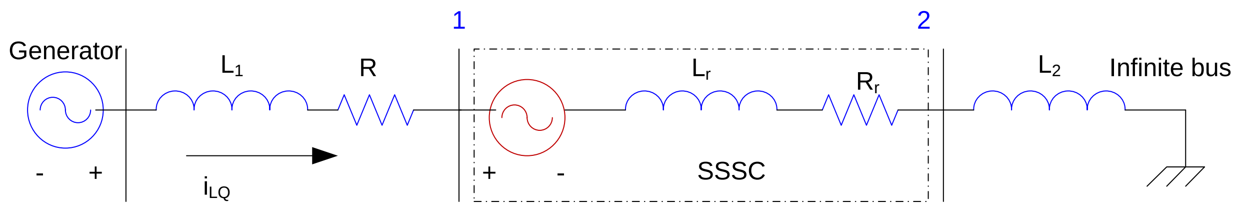


Figure 3-25: SSSC control schematic [12]

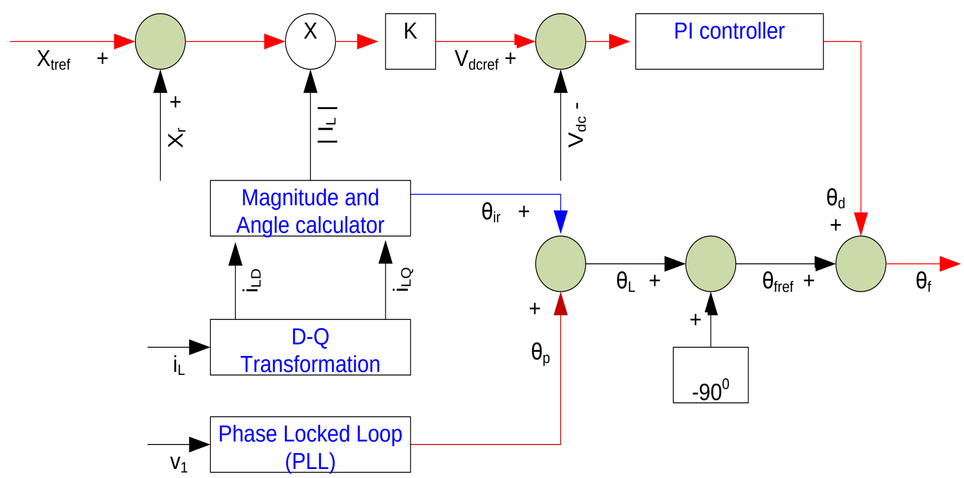


Figure 3-26: SSSC schematic and control loop [12]

3.5.10. SSSC control sequence (Figure 3-26)

- An instantaneous 3-phase set of line voltages at bus 1 is used to calculate the angle θ that is phase locked to the phase-a of the line voltage.
- An instantaneous 3-phase set of measured line currents is first decomposed into real and reactive components.
- The amplitude and the relative angle of the line current *θir* are then calculated.
- The phase locked angle θ_P and θ_{ir} are added to obtain the angle θ_l *which is the angle of the line current*.
- There are two control loops
- Since the SSSC voltage must lag the line current by 90°, a fixed angle equal to -90° is added to θ_l to obtain θ_{fref}
- In the auxiliary loop, the reactance demand X_{tref} is added to Xr of SSSC.
- The sum is multiplied by the magnitude of the line current and a constant to obtain V_{dcref}.
- The error between V_{dcref} and the actual value of V_{dc} is passed through a PI controller to obtain V_d. This quantity is then added to θ_{fref} to obtain θ_f of the inverter.
- The PI controller retains the charge on the dc capacitor by injecting a voltage nearly in quadrature with the line current.
- The real power exchange between the ac system and SSSC takes place if the injected voltage is not in quadrature with the line current, which either charges or discharges the dc capacitor.

- The PI controller then advances or retards the phase of the injected voltage relative to line current in order to adjust the power at ac terminals and keep the dc voltage constant.

3.5.11. SSSC Benefits

This device has a capability of generating controllable compensating voltage internally (inductive/capacitive range separately) of the magnitude of the line current. This device is operated at comparatively low voltage. This device is more effectively used in power oscillation damping. It has a capability and capacity to interface with external source of DC power in order to provide effective compensation to reduce the line impedance.

3.6. Principle of the series/shunt (UPFC) compensation

The UPFC encompassed with two SVS synchronous voltage source that is connected to common dc bus, one SVS in shunt connected and other SVS in series connected to provide compensation unified power flow in series and shunt mode of operations. Therefore the real power can take place between them as demonstrated in the Figure 3-27 [24].

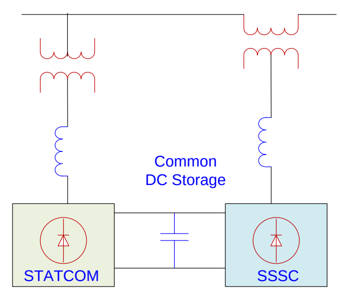


Figure 3-27: UPFC control schematic [12]

3.6.1. UPFC equivalent circuit

Figure 3-28 indicates the P_{pq} representing the real power exchange between shunt and series branches. V_{pq} represents the voltage through series compensator and Q_{pq} reactive power injected by the compensator and also shown in the circuit V_S sending and V_R receiving-end voltages.

Also, shown that $V_{seff} = V_S+V_{pq}$ Where, V_{seff} = Effective voltage V_S = Sending Voltage V_{pq} = Represents the voltage through series compensator

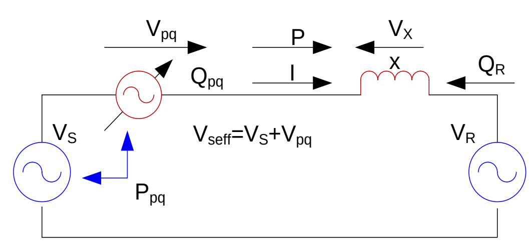


Figure 3-28: UPFC operations schematic [12]

3.6.2. UPFC phasor diagram:

Figure 3-29(a) indicates the Voltage regulation operations in UPFC. In the second Figure 3.29(b) indicates the Line impedance compensation and management in the UPFC controller. In the third Figure 3-29(c) phase shifting expressed in UPFC controller and in the Figure 3-29(d) indicates UPFC control parameters [45-47].

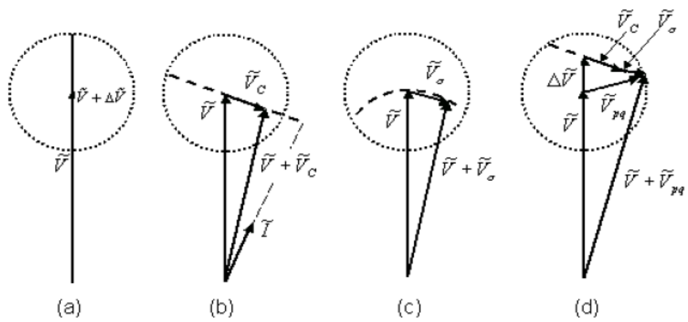


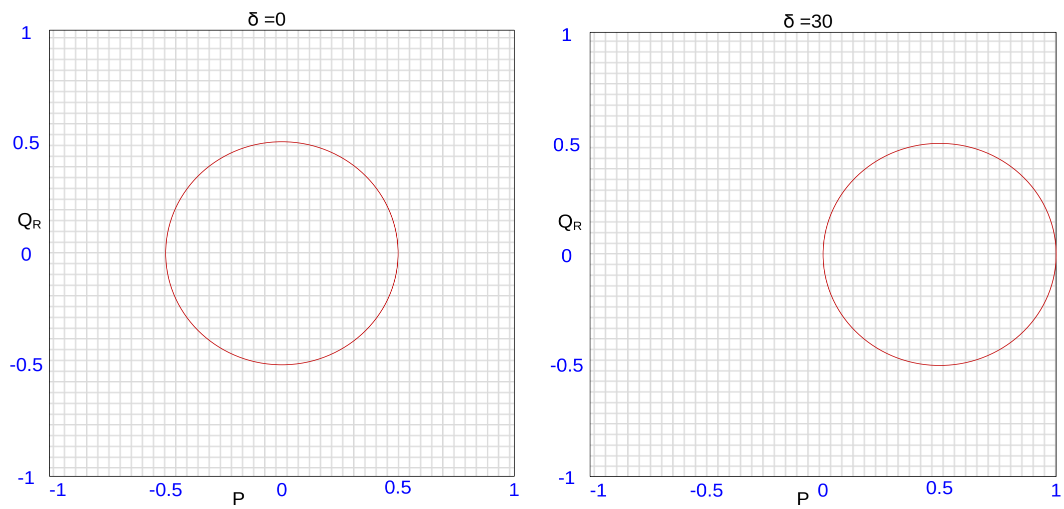
Figure 3-29: UPFC Phasor diagram [12]

3.6.3. UPFC operations:

Figure 3-30 expressed the UPFC operations summary in three scenarios, firstly, there is no power transfer, if the load angle is kept at 0 degree, secondly, if the load angle is adjusted at 30 degree, then the power will be transferred at 1.0pu. Thirdly if the load angle increased from 30 to 60 degree, then the power capacity will be increased from 1pu to 1.5 pu. Henceforth, the UPFC has a capability of transmitting power in either direction [81], [82].

P: can be negative and positive

Q: can be positive and negative as well.



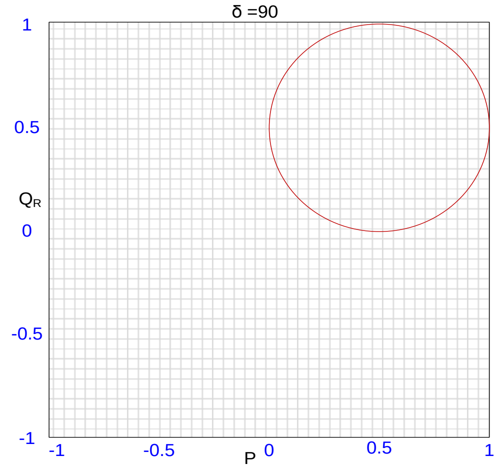


Figure 3-30: UPFC operations at various angles [12]

3.6.4. UPFC controller benefits:

- Investigation shows that the UPFC has an exceptional capability to control independently the real and reactive power flow at any transmission angle.
- The sending and receiving end voltages are provided by independent power systems that are able to supply and absorb real power without any internal angular change.
- In practice, the situation will be different depending on the change in load angle

3.7. HVDC application on the GCC power grid:

HVDC transmission is widely recognized as being advantageous for long-distance, bulk power delivery, asynchronous interconnections and long submarine cable crossings. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this mature technology. New converter designs have broadened the potential range of HVDC transmission to include applications for underground, offshore, economic replacement of reliability-must-run generation, and voltage stabilization. Developments include higher transmission voltages up to ± 800 kV, capacitor-commutated converters (CCC) for weak system applications and voltage-sourced converters (VSC) with dynamic reactive power control. This broader technology range has increased the potential HVDC applications and contributed to the recent growth of HVDC transmission. Figure 3-33 shows the ± 400 kV HVDC transmission line for the 2000 MW HVDC Power Project between KSA and Qatar as demonstrated in Figure 3-31 [1], [2].

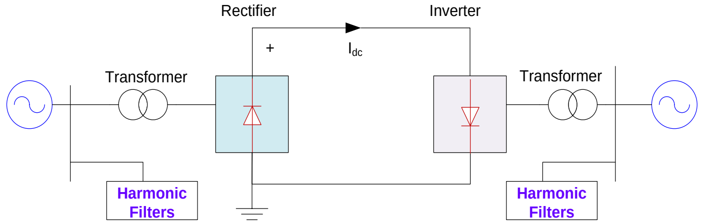


Figure 3-31: HVDC link from KSA to Qatar

3.7.1. HVDC link deliverables

Power flow on HVDC transmission systems accurately regulated, Constant Power, Constant frequency, reactive power control, AC voltage control. The most important aspect of HVDC is fast and stable controllability and bi-directional power flow at a given setting.

3.7.2. VSC based Transmission system -HVDC

HVDC accurately regulating Real and Reactive Power control, Dynamic Voltage Regulation. Also, providing Modular, expandability, and Black Startup Capability.

3.7.3. HVDC Characteristics:

There is no reactive power flow on DC line and there is no technical limit to the distance over which the power may be transmitted by cables or overhead transmission lines. The limit of the distance is economic, since the power losses in the transmission lines reach an unacceptable limit, when the practical conductor is used. HVDC power transmission line comprises with following benefits: (1) Full and fast control of the Power flow (2) No contribution toward short circuit level; (smooth control with VSC transmission) (3) Line losses are smaller. It is possible to bring more power through DC link without increasing fault level. (4) No reactive compensation for DC lines is required [82].

3.7.4. Principle of AC/DC/AC conversion:

In the converter stations two series connected 6 pulse converters (12-pulse bridge) consisting of valves and converters transformers are used to convert AC to DC to AC. A smoothing reactor in the DC circuit is also introduced to reduce harmonics distortions in the DC line and possible transient overcurrent. AC and DC filter are used to clean the harmonics currents into AC and DC circuits. By varying firing angle “Alpha” DC voltage can be controlled between two limits +VE and –VE.

- AC to DC rectifier (rectifier operations $0° < \alpha < 90°$)
- DC to AC inverter (Inverter Operations $90° < \alpha < 180°$)
- Extinction angle $\sigma = 180-\alpha$
- Maximum DC voltage when the “Alpha” is zero.

In the DC transmission system, the transmitted power is α difference in Vs and Vr and hence can be controlled by changing the VsDC and VrDC. Current can flow only one direction with given settings. Power is transported from rectifier to inverter and by altering the voltage the power flow direction is reversed [111].

- Inverter station is so controlled by Vd1 and Vd2, changing the angle of αmin =5° , αmax =15°±3° γmin=15°. To reduce the reactive power requirements by increasing Vd or reducing the α [77],[78]

3.7.5. HVDC/FACTS devices Challenges:

a) High Cost and value of HVDC:
b) Complexity of HVDC schemes/Circuits:
c) Dispatch and control of HVDC schemes:
d) Integration of HVDC with in an AC network
e) AC Harmonics filters
f) DC Harmonics filters
g) Operations of HVDC with ground return: The cost of HVDC is higher if it is permissible to operate with a single/HV metallic conductor. The power losses in the transmission line during earth return operations almost half of the LV metallic return conductor. Stability of network with multi in-feed at HVDC: If the HVDC were used for many more applications in a network then the issue of interaction between multiple HVDC schemes would become increasingly important [63], [64].

3.7.6. Proposed HVDC/FACTS devices link:

The prime objective on the GCC grid is to transfer bulk (1200MW) power from The Kingdom of Saudi Arabia to Kuwait and Qatar through the HVDC link. In addition to that, the HVDC link is also recommended to communicate with other GCC countries at different frequencies and voltages. After that the DC power was distributed to Kuwait 1500MW and 1500MW to Qatar equally. Hence to improve the Kuwaiti side power system a STATCOM device was recommended and simulated to meet Power system operational requirements as per defined parameters by the Kuwaiti power system authority. The UPFC also recommended delivering 2000MW power from UAE to Oman to meet both sides' power system operational requirements. All three models have been simulated successfully. The amount of Power that can be reliability transmitted over an AC and DC transmission systems depend on the transmission voltage as tabulated below [76].

Table 3.1 indicates the HVDC/HVAC Power delivery limitations:

HVDC SYSTEM		HVAC SYSTEM	
Voltage	MW	Voltage	MW
+/- 70kV	1100 MW	69kV	50-100
+/- 320kV	1200 MW	115kV	15-350
+/-400 kV	3100 MW	230kV	300-450
+/- 600 kV	6300 MW	345kV	1000-2050
		500kV	2000-3000

3.7.7. FACTS devices outcomes:

Figure 3-32 indicates the FACTS devices functionalities in order to meet power system control and operational requirements in general. These devices are contributing significantly to control three key power system parameters [70].

- **Load flow:** Series compensation has a small impact and shunt compensation negligible and the UPFC control devices have a strong impact on power system performance to enhance load flow control as demonstrated in Figure 3-35.
- **Stability:** Series and UPFC compensation devices have a strong impact on power system stability and shunt compensation has a medium impact on power system stability as demonstrated in Figure 3-35.
- **Voltage quality:** Shunt and UPFC compensation devices have a strong impact to improve line voltage quality and series compensation has a medium impact on the power system as demonstrated in Figure 3-35.

3.7.8. HVDC applications

- Back to back DC link two different frequencies systems are communicating with each other.
- Bulk Power transmission; if the fault at AC system this will not trip the unit at the converter stations asynchronous DC link isolates the Power system from the AC system.
- Bulk power can be transmitted up to 1200MW
- (V,T) variations do not affect the DC link
- DC Power cables are cheaper, above 50 Km with Power level 1000-2000 MW
- AC system required forced cooling; high heat increased the dielectric losses at EHV cables.
- Stabilizing AC power system by modulating DC power flow.

3.7.9. HVDC and FACTS devices benefits

FACTS devices contribute as listed below

- To improve voltage quality
- To improve power system stability margin
- To improve and enhance load flow

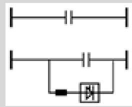
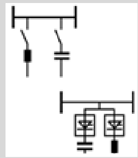
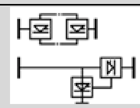
Principle of Operating parameters	Device	Scheme	Impact on GCC Power System Performance: Load Flow	Stability	Voltage Quality
Series Compensation: To Vary the power transmission line impedance	FSC: Fixed Series Compensation		X	X X X	X
	TPSC: Thryrister protected Series Compensation		X	X X X	X
	TCSC: Thryrister controlled Series Compensation		X X	X X X	X
Shunt compensation: To control the power transmission line voltage	MSCR: Mechanical Switched Capacitor/ Reactor)		X	X	X X
	SVC: Static Synchronous Compensator		X	X X	X X X
	STATCOM: Static Synchronous Compensator		X	X X	X X X
Series and Shunt compensation: to control the load flow	HVDC (B2B, LDT)		X X X	X X X	X X
	UPFC: Unified power Flow Controller		X X X	X X X	X X X
Influence Legends	X: Low or no	X : Small	X X : Medium	X X X: Strong	

Figure 3-32: FACTS devices performance benefits

HVDC contribute as listed below:

- DC lines simpler, cost-effective and having two conductors instead of three conductors.
- Further OH lines required 2/3 insulators, towers, cheaper and narrower.
- Narrower right of way is required.
- Both lines have the same loss per conductor
- DC cables are better than the AC.
- Figure 3-33 indicates the cost and performance benefits of the HVDC system against the HVAC overhead transmission line.
- If the OH transmission line is above then 700 kilometers then the DC link is strongly recommended.
- Underground cables if the transmission cable is above then 50 kilometers then the DC cable is strongly recommended.

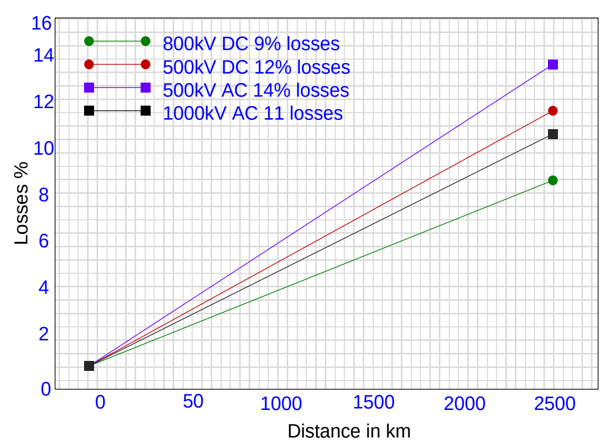


Figure 3-33: HVDC and HVAC comparative Analysis

Figure 3-33 indicates that 800kV DC transmission line has 9% losses for 2500KM, whereas 500kV DC line is carrying 12% losses. As a result, it reflects that high DC voltage has less transmission losses compared to 500kV DC line. Figure3-36 also indicates a similar pattern that 500kV AC transmission line has 14% losses, whereas 1000kV AC line is carrying 11% losses. As a result, it reflects that high AC voltage transmission line has less transmission losses compared to 500kV AC line [70-74]

3.7.10. Economic consideration of HVDC and FACTS devices

Given below Table 3.2 is briefly indicating a comparison cost analysis of HVDC against FACTS devices to meet sustainable operational requirements [1].

Table 3.2 HVDC/FACTS devices cost comparison

No	Throughput-MW	HVDC 2 terminals	FACTS
1	200 MW	40-50 Million Dollars	5-10 million Dollars
2	500 MW	75-100 Million Dollars	10-20 Million Dollars
3	1000 MW	120-170 Million Dollars	20-30 Million Dollars
4	2000 MW	200-300 Million Dollars	30-50Million Dollars

3.8. Summary

The GCC power grid encompassed six countries and each country power transmission is behaving differently at different locations on the GCC power grid. Herewith, based on their current operating parameters FACTS/HVDC devices control systems are configured in order to meet shunt and series compensation on the GCC power grid. Firstly this chapter describes the EHV power transmission line model and its operating and control parameters. Secondly, shunt and series compensation and its operating and control parameters viabilities and criticalities are demonstrated effectively. Insofar, shunt and series compensation capacitive and inductive modes of operations are also described thoroughly. It has been also identified and determined how to transfer maximum real power through the power transmission line and, the amount of shunt or series reactive power compensation is required.

Secondly, this chapter describes the series compensation and its operating parameters viabilities and criticalities. Herein both capacitive and inductive modes of operations are described by putting its security and operational criticalities into consideration. It has been also identified and determined that to transfer maximum power, the amount of series reactor is required on transmission line as defined by the degree of shunt/series compensation. Thirdly, this chapter also described the UPFC and HVDC operational versatility at different operating angles on the GCC power grid. This chapter also demonstrates the techno economic analyses respectively.

CHAPTER 4

FACTS controllers tuning and optimization by using PID, PD, PI configuration parameters

4.1 Introduction

The proposed work is a control loop optimization technique, which has been adopted to fine-tune and optimize various FACTS devices (STATCOM, SSSC, and UPFC,) performance by using *Douglass J. Cooper* PID, PD, PI controller constant and variable control parameters at different locations on the GCC power grid during any undesired operating condition. The primary objective is to identify, determine and address vulnerable areas and operating boundaries of different control loops of target FACTS devices that are in operation at a time to enhance or sustain along with its existing operational performance. These devices will directly or indirectly impact on network performance (improving voltage quality, power flow and power stability) by providing time based adequate reactive power compensation when required.

The research work is organized as follows: after the introduction section, controller optimization technique, the PID, PD, PI controller scope, tuning framework and controllers' features are described in Sections 4.2, 4.3, 4.4 & 4.5. The PID, PI, PD controllers tuning methodology, simulated models, observation and results/conclusion are presented in sections 4.6, 4.7 4.8 and 4.9. To establish and implement various PID and PI control loops tuning and optimization techniques are used in order to enhance power system's controllability and strong communication links in between the STATCOM, SSSC & UPFC devices at different location on the GCC power grid. Listed below are the 10 control domains that need to be understood prior to executing any tuning process in order to obtain the desired results.

1) Define constant and variable control parameters for tuning purposes which are used to control STATCOM, SSSC, and UPFC devices operations.
2) Define and determine the tuning purpose of controller's in electrical control system operations.
3) Define and determine the STATCOM, SSSC, and UPFC devices operations response against the control response.
4) Determine the importance of a quarter-wave decay ratio curve as it relates to controller tuning.
5) Determine the different waveforms result against the process operational changes
6) List the preliminary steps for tuning a controller response
7) Difference between "open loop" and "closed loop" tuning.
8) How to become familiar with the open loop tuning.
9) How to become familiar with trial and error method of tuning used in a closed loop.

10) How to become familiar with ultimate method of tuning used in closed loop.

The tuning method is to adjust the control parameters (gain/proportional band, integral gain/reset, and derivative gain/rate) at optimum values in order to produce desired and proper control response to fix electrical power process upset. The process upset is occurring whenever there is a large disturbance caused by a sudden change on the process input; process load and process set point. However in order to obtain below mentioned process dynamics it is very important to properly tune the controller to meet the operational requirements.

1) Minimize or eliminate power system control deviations.
2) Maintain power system's operational stability.
3) Ensure power system operations safety and security.
4) Maintain generation, transmission and distribution demands without any constraint.

4.2. Novel Optimization Control Technique (*Douglass J. Cooper)*

This work presents the novelty of PID and PI feedback controllers in order to establish centralized or de-centralized control of the FACTS devices by using a D.J. Cooper optimization technique. Figures 4-1 & 4-2 indicate the centralized and de-centralized control function blocks. PID and PI controllers can also be used when the device displays non-self-regulating behavior at different locations on the GCC power grid. By implementing a sensitive process control based method this will help to distribute the control signal to operate and maintain all three devices in parallel operations at time to establish centralized control or independently to establish de-centralized control topologies. These controllers can deliver robust and sustainable distributed control based on their disturbance rejection performance on the GCC power grid. Based on the D.J. Cooper optimization technique PID and PI controllers can be configured and retuned as illustrated [13].

PID and PI controllers compute a controller output (COP) value as per defined sample time "T" to the final control element to adjust the gating response of the converters. The calculated output from the PID & PI controllers algorithm is influenced by the controllers error e(t) and optimized tuning parameters. Firstly, the PID controller comprises of three tuning parameters P, I and D which need to readjust at their optimum value in order to obtain sustainable controller response. PID controller is complicated with added challenges to tune and design controller to attain an optimum response to meet stringent operational requirements on the GCC power grid. Secondly, the PI controller comprises of two parameters P & I, these also need to readjust at their optimum value to obtain sustainable controller response. This is a simple and straightforward tuning technique as adopted in [20],[21]. The equation below (4.1) and (4.2) demonstrate how to obtain an optimum response of the PID and PI controller [20].

Equation (4.1) and (4.2) demonstrate optimized response of the PID and PI controllers.

$$COP = COP_{bias} + kc'e(t) + \frac{kc}{Ti}\int e(t)dt + kc'Td\frac{de(t)}{dt} \qquad (4.1)$$

Where:

COP= controller output signal, COP_{bias} =set by bumpless transfer function (controller bias)

SP = setpoint, PV= process variable, kc = a tuning parameter, controller gain value, Ti = a tuning parameter, reset time, Td= a tuning parameter, derivative time.

$$COP = COP_{bias} + kc'e(t) + \frac{kc}{Ti}\int e(t)dt \qquad (4.2)$$

Where:

COP= controller output signal, COP_{bias} =set by bumpless transfer function (controller bias or null value), e(t) = controller operational error (SP-PV) SP = setpoint, PV= process variable, kc = a tuning parameter, controller gain value, Ti = a tuning parameter, reset time, Td= a tuning parameter, derivative time.

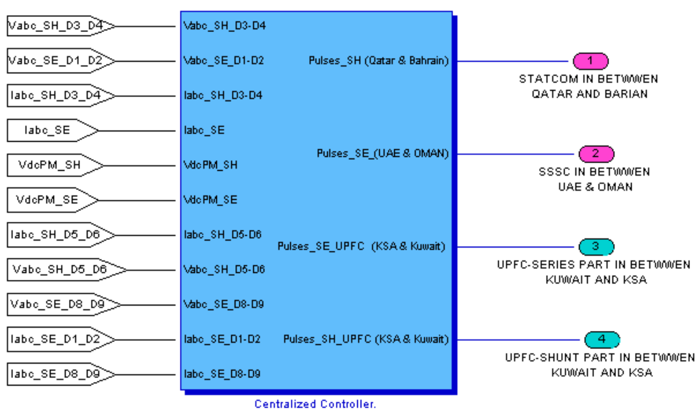


Figure 4-1 Function block of centralized control loop [Matlab]

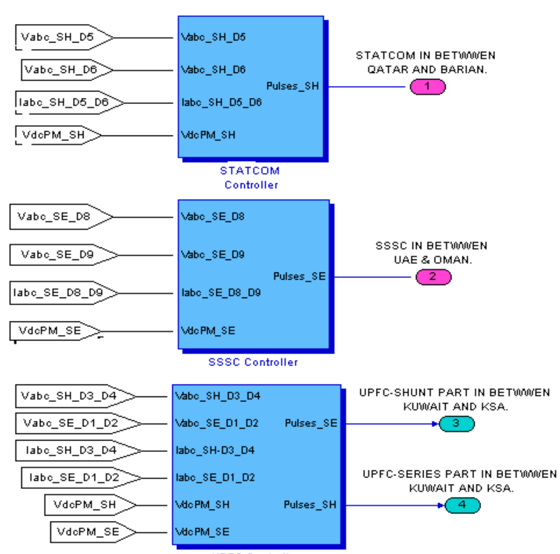


Figure 4-2 individual function block of de-centralized control loop [Matlab]

There are three steps which can be used to determine the nature period of oscillation of the process change in order to optimize the control system parameters. Step 1: in the first stage the controller integral time at its maximum and controller derivative at its minimum and providing proportional only control. After that reduce the proportional band until oscillation begins. Measure the period of this oscillation (also called the natural period) as the time between two successive crests or valleys. Step 2: in the second stage set the controller derivative time at 0.15 times the natural period, and change the controller integral time at 0.4 times the natural period. After that observe the change of oscillation, it will indicate that 25 % decrease. If the new period of oscillation is shorter than this, after that reduce the controller's derivative time, if the period is longer increase the integral time. Step 3: in the last stage, readjust the proportional band to achieve the desired degree of damping (the amount of correction to a process upset which, when too high or low, it indicates as either overshoot or sluggishness respectively)[25].

4.2.1 PID, PI Controllers optimization implementation Scope:

A customized control configuration technique has been developed by using P, I and D control variables to adjust the FACTS devices' time based response, in order to address power transmission contingencies by implementing centralized and decentralized control. Based on these control variables the STATCOM, SSSC and UPFC will generate response against the deviation e.g. line voltage, impedance, and power flow transfer at different locations on the GCC power grid. These devices will inject or absorb reactive power based on controller compensation response (+/-) through their inherent (capacitive or inductive) mode of operations as well as to share compensation loads at different locations on the GCC power network. Table 4-1 indicates the STATCOM and SSSC control loops variables. These variables are used to configure a time based transfer function of each device control loop. A Matlab model is used to evaluate transfer function of each control loop to identify and determine the optimum value of each parameter which is used to control the STATCOM & SSSC operations. In linear operating range of the STATCOM the terminal voltage (V_T) can be denoted from figure 4-3 in terms of internal voltage V and the reference voltage V_{Ref} as given below[1], [2].

$$V_T = V\frac{1}{1+G_1G_2HX} + V_{Ref}\frac{G_1G_2X}{G_1G_2HX} \qquad (4.3)$$

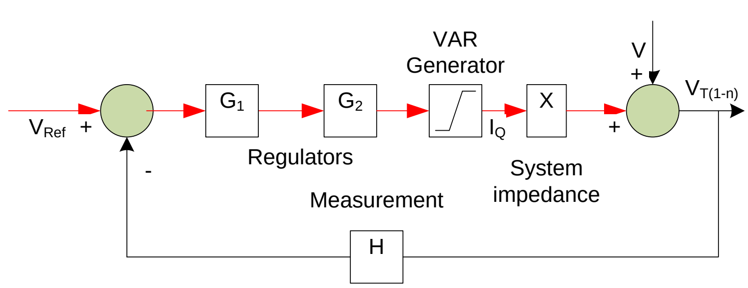


Figure 4-3 transfer function block diagram of the compensator [1]

Primary objective is to regulate the system voltage against the variation by implementing optimum value of PI controller as described in section 4.5.1 & 4.5.2. Let presume V_{Ref} = 0 based on that consider small deviation. Then the terminal voltage ΔV against the power system ΔE_s can be denoted in equation (4.4). Table 4.1 indicates the input value of the above mentioned control loop. Figure 4-4, 4-5 & 4-6 indicates the Bode-plot representation of the compensator control elements.

Table 4-1 STATCOM and SSSC control modeling parameters

Parameter	Definition	Typical value
T_1	Main time constant of the PI controller	10-50 ms
T_2	Time constant for Amplitude measuring circuit -firing delay	8-16 ms (SSSC) 0.50 ms (STATCOM)
T_d	Transport lag of the VAR generator	2.5 ms for TCR 5.0 ms for TSC 0.2-0.3 ms for converter
Xs	Reactive part of the system impedance	4.761 for strong system 9.522 for weak system
K_D	**Regulation slope**	1/0.9 for 10% Slope

Step # (1) STATCOM/SSSC control transfer function is demonstrated by using equation (4.4).

$$G_{1(s)} = \frac{K_D}{1+T_{1s}} \qquad (4.4)$$

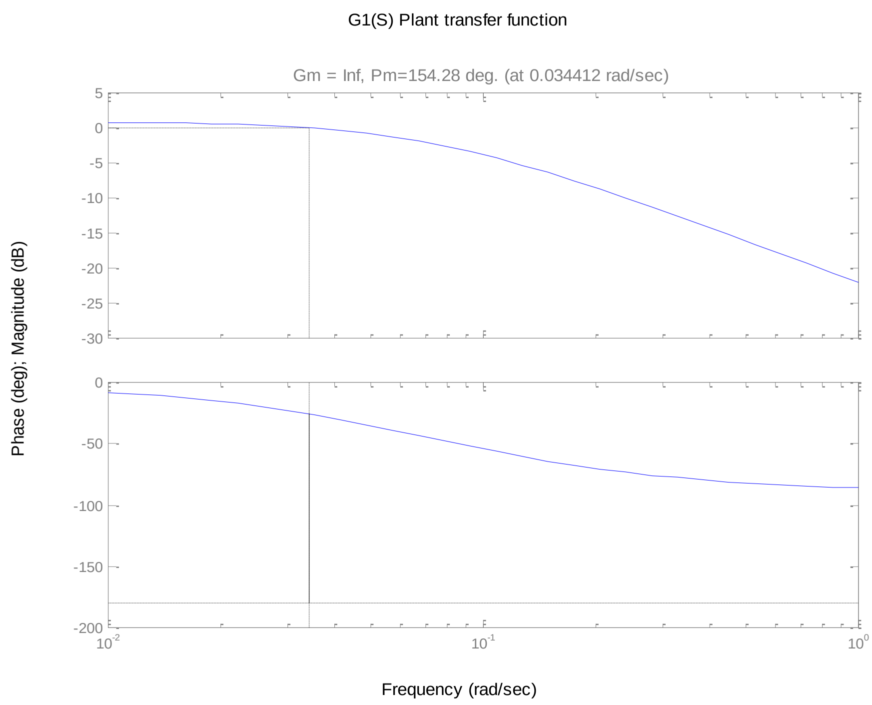


Figure 4-4 indicates the simulated values of $G_{1(s)}$ [Matlab]

Step # (2) STATCOM and SSSC control Transfer Function is demonstrated in equation (4.5)

$$G_{2(s)} = e^{-T_d} \qquad (4.5)$$

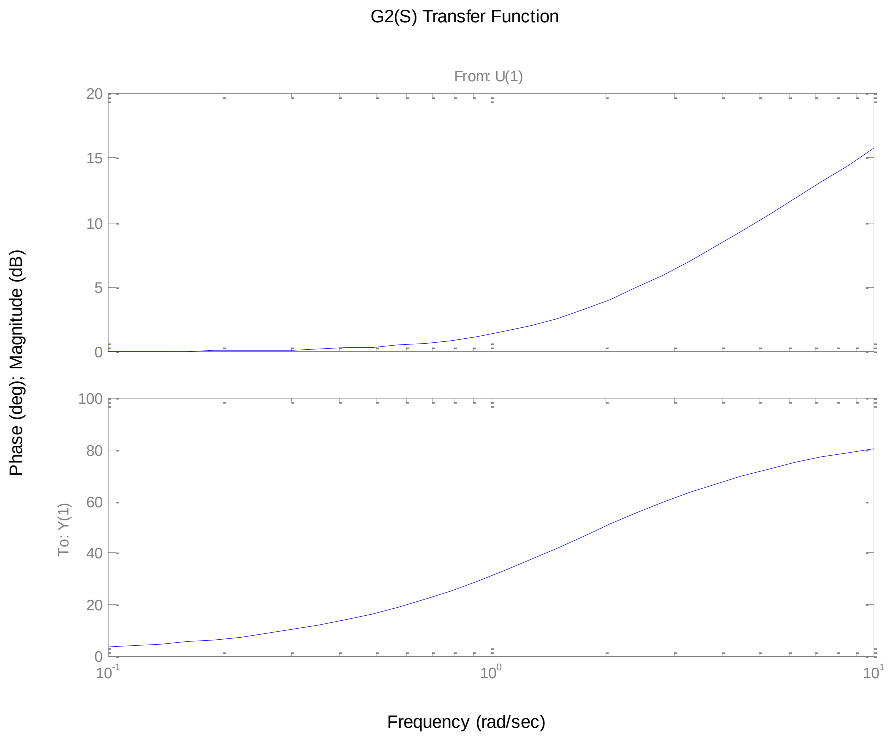


Figure 4-5 indicates the simulated values of $G_{2(s)}$ [Matlab]

Step # (3) STATCOM/SSSC Control function is demonstrated in equation (4.6).

$$H_{(s)} = \frac{1}{1+T_H S} \qquad (4.6)$$

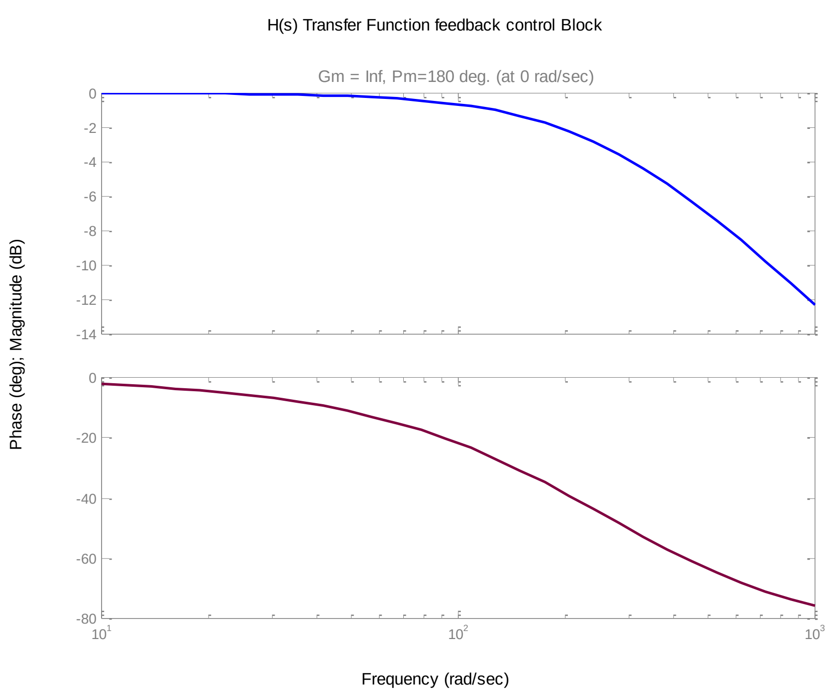


Figure 4-6 indicates the simulated value of $H_{(s)}$ [Matlab]

This is a final control function of STATCOM & SSSC control block for implementation which is demonstrated in equation (4.7)

$$\frac{\Delta V}{\Delta E_s} = \frac{1}{1+G_{1(s)}G_{2(s)}H_{(s)}X_s} \qquad (4.7)$$

4.3. PID, PD, PI Controller Tuning Framework:

A. Determine the Control Loop Characteristics

By using knowledge of open and closed control loop tuning and optimization characteristics, controller mode principles and adjustment methods, operation of the control system can be observed and examined to obtain high a level of operational accuracy. Based on these observations the tuning of control parameters enables the controller to compensate for load changes or disturbances to eliminate error (deviation). A controller must be tuned to match the process dynamics by implementing the following parameters' control values at an optimum level to achieve the required objective [17].

a) Understand the integral control action (I)
b) Understand how the error can be eliminated in a PI-controller
c) Define integral gain and integral time.
a) Understand the derivative control action (D)
b) Understand how the error can be eliminated in a PD-controller
c) Define derivative gain and derivative time.

Purpose:

1. To increase sensitivity of the control.
2. To provide better control of a process by reducing the time lag in a control system.

Merits of these parameters are:

A. Better control of the primary variable.
B. Primary variable will be less affected by disturbance.
C. Faster recovery from disturbance.
D. Reduce the effective magnitude of time lag.

B. Integral control (I)

Integral action avoids the offset created in proportional control only by bringing the output back to the set point. It is an automatic rebalancing of the electrical power system operations, which operates as long as an error exists. Therefore, integral control responds to the duration of the error as well as its magnitude and direction. This is never used alone; rather, it is combined with proportional control. The main purpose of integral control is to eliminate the offset or the steady-state error. This is also referred to as an automatic reset action. Figure 4-7 demonstrates the integral control response, if the input signal (process error Ep) is positive; the integral amplifier output signal (control signal) will increase. If the input signal (process error Ep) is negative, the integral amplifier output signal (control signal) will decrease. If the input signal (process error Ep) becomes zero, the integral amplifier output signal (control signal) remains at the same level that is why it keeps the output of the controller as it is[25], [26].

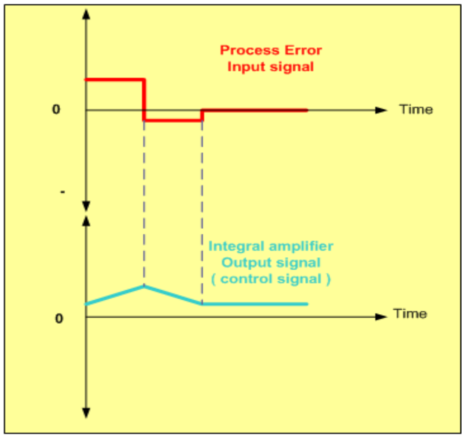


Figure 4-7: PI control loop's Process error Ep against Integral AMPL output [17]

C. Integral Gain (Ki) and Integral Time (Ti) Control:

It automatically minimize or eliminates the steady-state error or offset by giving the controller output to the control element until there will be no longer an error with good transient response. Herein an integral gain (Ki -gain of the integral amplifier) is the number of times the input signal amplitude is repeated at the amplifier output in a period of one minute and it has been expressed in Equation (4.8). Secondly an integral Time (Ti-time on the integral amplifier) is the time required for the input signal amplitude to be replicated at the amplifier output as expressed in Equation (4.9).

$$K_i = {}^{repeats}/_{minute} \qquad (4.8)$$

$$T_i = {}^{minute}/_{repeats} \qquad (4.9)$$

It is very important to understand that the "smaller the time value, the faster the integral action". These responses are described in Figure 4-8. Firstly "A" Too-Short if the system response will overshoot the set point and a continuous cycle may result. Secondly, "B" Too-Long if the system will not perform at maximum efficiency. Thirdly, "C" Correct" if the system response will have a quarter-wave decay ratio curve an indication of good control.

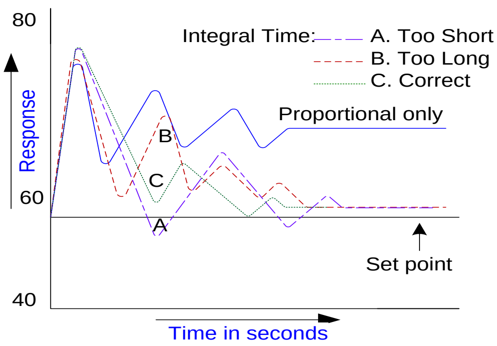


Figure 4-8: PI Control Loop Oscillations against the set point[17]

D. Derivative Control (D) Action PD (Control):

Derivative control is an action which is proportional to the rate of change of the process error. It can improve the transient response and stability of an electrical process control system. This is also called, rate or anticipatory control. The derivative control cannot be used alone in an electrical process control system because no signal is produced when there is a steady-state error (offset). This is very useful in controlling the power system processes with a sudden change of set point or load. However it does not eliminate the steady-state error or offset. Herein with derivative action, the faster the rate of change of the process error, the higher the magnitude of the control signals. With noise, which usually has a very fast rate of change, this may be amplified so much by the derivative control action resulting in a very noisy control signal and stability is seriously affected. Figure 4-9 describes the PD controller responses, this is very important to understand and determine as followed.

1. When the input signal (process error Ep) is increasing (positive slope), the derivative amplifier output signal is positive and this will be proportional to the input signal.
2. When the input signal (process error Ep) is decreasing (negative slope), the derivative amplifier output signal is negative and proportional to the input signal.
3. When the input signal (process error Ep) is constant, the derivative amplifier output signal is zero.
4. Therefore the amplifier output signal (control signal) would be a non-zero only when the process error is changing.

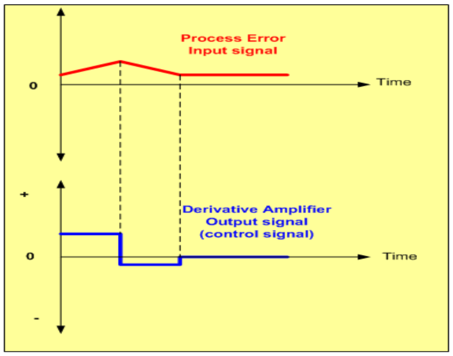


Figure 4-9: PD control loop's Process Error Ep Figure [17]

E. Proportional plus Integral plus Derivative (P I D) Controller:

Sections 4.5 has illustrated the tuning methodology and section 4.6 explained the PI controller behavior and configuration perspective in multidimensional to meet FACTS controller's operational requirements as described. This section is focused on PID controller behavior and various response in order to maintain operational requirements more accurately, what explained in PI and PD controllers'. It has been also learned that output of PID controller is a linear combination of P, (proportional) I (integral) and D (derivative) modes of control system. Herein the PID controller encompassed multifaceted operational features to all aspects of electrical power system operations. However, the PID controller responses are identified and determined in order to obtain process control objectives more precisely comparable to PI and PD controllers (Direction, Magnitude, Duration, and change). It has been learned that the PID controller is offering two types of strategic control operations. Figure 4-10 explained the Interacting PID control topology, it demonstrates when both D and I control actions are performing in series. This is called a series configuration at the first part of the PID control topology.

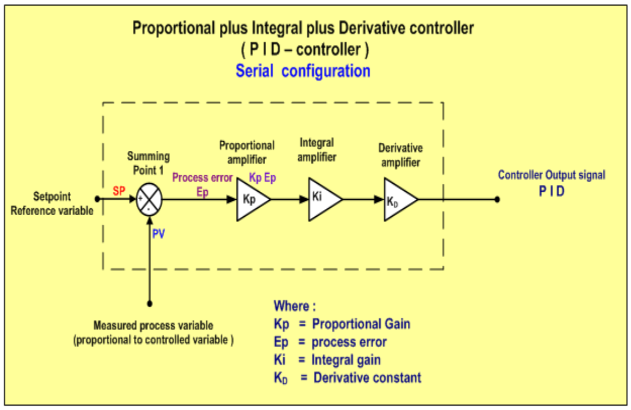


Figure 4-10: Interacting PID Controller [17]

Figure 4-11 Control Loop Oscillations; this is an indication of good control which is being demonstrated by using (PI) proportional-integral control and (PID) proportional-Integral-derivative control.

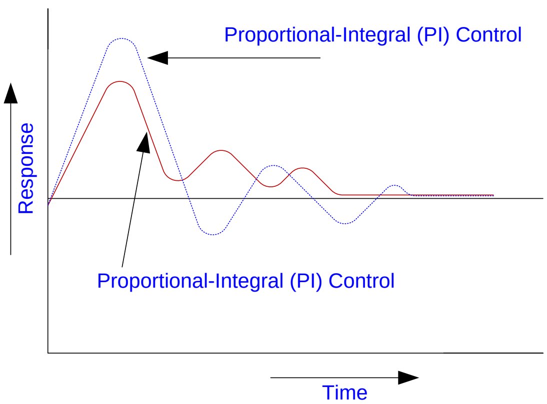


Figure 4-11: PI and PID control loops behavior [17]

4.4. Control Loop Tuning Methodology

4.4.1. Open Loop Tuning Techniques:

In order to execute open loop tuning process, it is very important to analyze and determine the following parameters to obtain the required results.

1. Differentiate open loop and closed loop process control system parameters.
2. Define process control Feedback of target loop.
3. Differentiate and list all possible Negative and Positive Feedback.
4. Define the process characteristics as mentioned, Dead Time, Gain and Time constant.

The output variable (or the controlled variable/ measured variable) does not have any influence on the input variable (or the manipulated variable). It requires that the controller will be on manual as described in Figure 4-11. Open loop methods such as the Reaction curve minimize disturbances to the process. During the tuning process, only a single upset is imposed on the controller process changes as described in Figure 4-12. Secondly, creating a step change to produce a reaction curve that is used to find the values needed to adjust the controller. However, this method gives more precise data about the dynamics of a feedback control system and usually gives comparatively better tuning results.

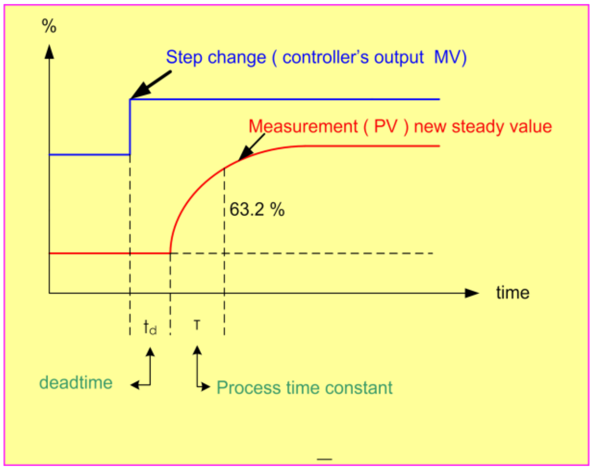


Figure 4-12: Process Reaction Curve [17]

4.4.2. Closed Loop Tuning Techniques:

If the controller is on automatic, the loop is closed as demonstrated in Figure 4-13. In order to achieve proper tuning parameters simulated disturbances are introduced to the process to synthesized process parameters as per requirements. During the tuning process, Set-point changes are repeatedly introduced to find the appropriate setting of the control parameters of (P, I, D) to produce the quarter wave decay ratio curve. The output variable (or the controlled variable / measured variable) has an influence on the input variable (or the manipulated variable) with given define parameters.

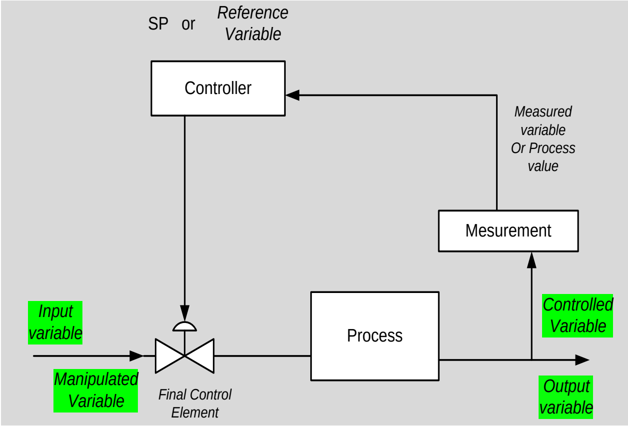


Figure 4-13: Close Loop Tuning Diagram [17]

4.4.3. Ultimate Method Tuning Technique

This is a closed loop tuning method with the controller in an automatic control mode, there is a continuous sustained oscillation result. In this procedure firstly, there is the identification of Ultimate proportional gain (Ku), which is the initial setting of proportional gain to produce the continuous sustained oscillation. Secondly there is the identification of an Ultimate period (Pu) which is the period resulted on the continuous sustained oscillation, basically the time between successive peaks as demonstrated in Figure 4-14.

Firstly, there is the recording of all the controller settings so if there are any unexpected constraint produced these can be returned as they are. Secondly, there is the adjustment of the integral and derivative control values to their minimum setting and the putting of the controller in an automatic control mode of operations and an adjustment of the proportional gain to a point where a set-point change will cause a small oscillating response. Observe the process response as soon as an upset is observed return to set-point. In the first attempt, if the response curve damps out, as in Figure 4-15, the gain is too low (proportional band is too wide).

Increasing the gain (or narrow the proportional band), imposes a set-point change and observe the response. In the second attempt, if the response curve over-oscillates as in the Figure 4-16, the gain is too high (proportional band is too low). One should adjust the gain to a lower setting (or the proportional band to a wider value). One should continue to make adjustment to the proportional band until the process response curve produces a continuous sustained oscillating response for three or four cycles. The proportional setting that produces this process response is the ultimate gain or ultimate proportional band. One should determine the ultimate period. This value is determined by timing in minutes, the interval between the peaks or by calculating the intervals from the divisions on the graph of a continually oscillating process response [89], [90].

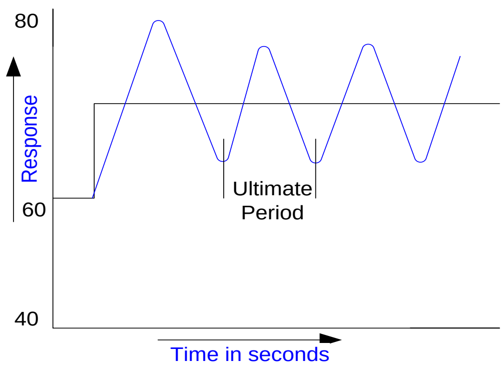


Figure 4-14: Ultimate Loop Tuning Method [17]

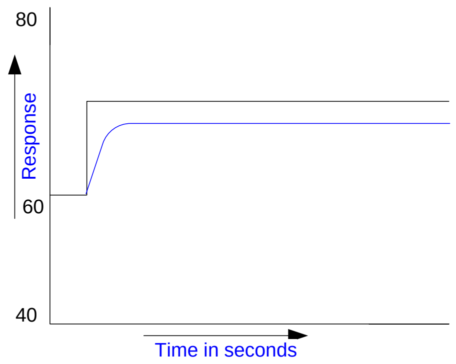


Figure 4-15: curve with no oscillation may not achieve set point [17]

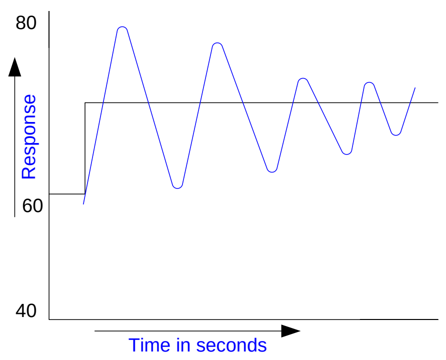


Figure 4-16: curve with high oscillation _ is unstable [17]

4.4.4. Trial and Error Tuning Method

As electrical power control system engineer, one should tune the FACTS control devices control loops by using trial and error method in order to achieve set-point changes. Herein, it has been observed that once a loop is tuned properly to good set point response, the responses to upsets are usually very sluggish. It also witnessed that a good set point tuning does not automatically result in good recovery from upsets. Wherein, these upset usually the source of off-spec product and its inconsistency. There is a well-known controller tuning criterion which demonstrates a decay ratio of ¼ following a set point change as a power system operations requirement. This is also known as quarterly-wave decay. Principally, if a control loop is oscillating due to set point change each forthcoming peak variation should be one-fourth of the previous peak. This oscillation could be negative or positive on the same side of the set point. On each half cycle of the controller oscillation, the amplitude of difference of the oscillation should be decreased by roughly one-half, which indicates the total decrease one-fourth for a full cycle as indicated in Figure 4-17. Figure 4-18 described the nine shades of decay ratio matrix, which demonstrates (PI) control parameters suppose to be changed in order to meet set-point changes at different location on the GCC power grid. This is strongly recommended to use modern tools to analyze a loop to identify and determine operational barriers, which are limiting strategic and precise operations. Herewith, there are three steps can be used to determine the nature period of oscillation of the process change. Each box of the matrix shows typical response curve. Response curve's decay ratio and period are compared with a curve in the matrix based on the deviation fine tuning adjustments are recommended.

- The horizontal rows indicates period
- The top row indicates the curves with a period of less than $1\frac{1}{2}$ times the integral.
- The bottom row indicates the curves with a period of more than $2\frac{1}{2}$ times the integral.
- Vertical rows in the matrix represent the decay ratio, from less than a quarter-wave in the left side, to more than quarter-wave in the right column.

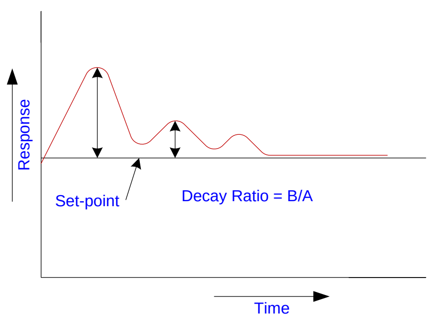


Figure 4-17: Response to a set point change typical behavior

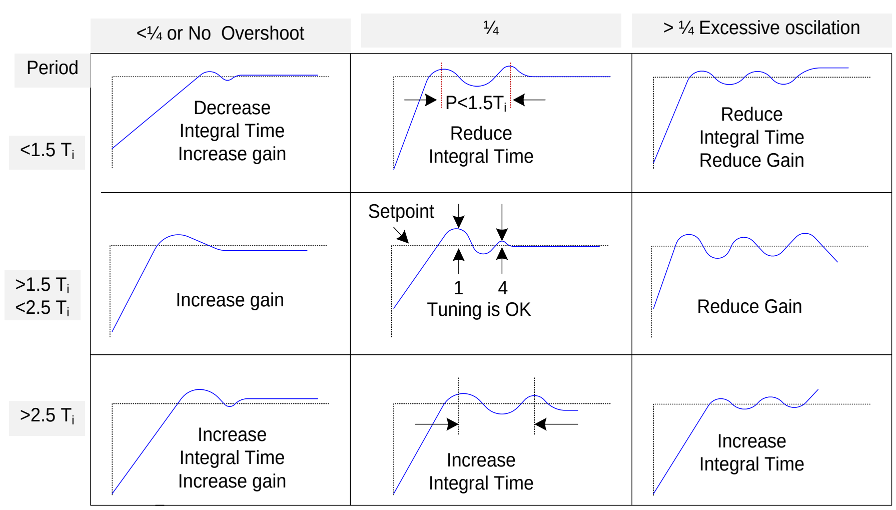


Figure 4-18: Decay Ratio Matrix [17]

4.5. PI controllers modeling and simulation technique:

Based on *Douglass J. Cooper,* PI, PD PID control and optimization technique is an intricate netted well-controlled model developed by incorporating P, I and D configuration parameters. These values are selected by using closed-loop and Trial-Error tuning methods to increase or reduce the controller response against each control device's operating and control boundaries. Based on these methods large numbers of PI control models have been developed and simulated to investigate and obtain the most optimum value of each configuration parameter(s) (P, I and D). After getting optimum values of these parameters a time domain PI control Algorithm has been developed and simulated by using a generic excel mathematical workbook to produce the desired results. Below the PI control model's Algorithm indicates the functionality of the measurement and control model's configuration parameters [25], [26].

(Input parameters of the PI control model

Proportional Gain (Kp)= B1; Integral Time (Ti)=B2; Set point= B4;
STATCOM & UPFC PI Control models in between the KSA and Kuwait + Qatar and Bahrain

Model-1 B1 = 0.32; B2 = 0.6 and B4 = 400kV; Model-2 B1 = 0.36; B2 = 0.8 and B4 = 400kV Model-3 B1 = 0.38; B2 = 0.9 and B4 = 400kV;

SSSC PI Control models in between the UAE and Oman
Model-1 B1 = 0.32; B2 = 0.6 and B4 = 220kV; Model-2 B1 = 0.36; B2 = 0.8 and B4 = 220kV Model-3 B1 = 0.38; B2 = 0.9 and B4 = 220kV

Calculation of the models framework:

PV= B9, B10, B11…..B58;

Error= C9, C10, C11… C58; Absolute Error=D9, D10, D11….D58;

Output=E7, E8, E9…E58; Ki (Integral Gain)=F7,F8, F9,….F58

Error =SP-PV; PV = Controller output after third iteration; Output = Kp x Error;

Absolute Error = ABS(Error); Integral gain: = $iT_0, iT_1, iT_{2.....}iT_{58}$ (As defined below)

1st iteration iT_0 = Output x Integral time;

2nd iteration iT1 = iT_0 +(output - iT_0) x Ti;

3rd iteration $iT_2 = iT_1$ + (output – iT_1) x Ti……..58th iteration iT58 = iT_{57} + (output – iT_{57}) x Ti;

Controller Error: C9 = B4-B9, C10 = B4-B10, C11 = B4-B11….C58 = B4-B58
Controller output: E7 = 0, E8 = 0 E9= B1x C9, E10= B1xC10, E11= B1xC11 … C58 = B1xB58
Integral Gain: F7 = E7xB2, F8 = F7+(E8-F7)xB2, F9 = F8+(E9-F8)XB2, F10 = F9+(E10-F9)XB2,… F58 =F57+(E58-F57)XB2
Process Variable: B9 =0, B10 = E7, B11 = E8, B12 =E9… B58 = E55
Absolute Error: D9 = ABS(C9), D10 = ABS(C9), D11 = ABS(C9),… D58 = ABS(C58)

Appendix 4.A, 4.B, 4.C, 4.D, 4.E and 4.F illustrates the 58 rows and six columns (A, B, C, D, E & F) of excel mathematical workbook sheet. B1, B2, & B3 rows indicate the inputs of the PI control mathematical model-1. A6, B6, C6, D6, E6, & F6 columns indicate the six main calculations parameters of the PI control mathematical simulation model. These six parameters are calculated carefully based on the formulas as given in the above Algorithm. The workbook sheet is configured in an automatic mode by plugging in P, I, and Set point inputs. Based on control deviation the workbook sheet will automatically simulate and produce the results. These values are identified and determined by using Closed-Loop and Trial & Error tuning methods of the PI control model [20].

4.5.1. STATCOM & UPFC distributed PI control:

A PI controller's detailed calculations are performed and mathematical model developed and synthesized by incorporating new set of PI configuration values as demonstrated in Appendix 5.A & 7.A in order to control the 400kV line voltage of the AC power system in between the Qatar and Bahrain as well as KSA and Kuwait on the GCC power network. In the first model (Appendix 9.A) both STATCOM and UPFC PI controllers are configured by incorporating first set of P & I values(P=0.32; I= 0.6 and SP=400kV) to inject and absorb minimum reactive power based on +/- 2% deviations. Based on this deviation the PI control model oscillated and took 21 iterations to stabilize the control loop by adjusting the minimum reactive power compensation as demonstrated in Appendices 5.A & 7.A.

In the second model (Appendix 9.B) both STATCOM and UPFC PI controllers are configured by incorporating 2nd set of P & I values (P=0.36; I= 0.8 SP=400kV) to inject and absorb medium reactive power +/- based on +/- 4% deviations. Based on this deviation the PI control model oscillated and took 19 iterations to stabilize the control loop by adjusting the medium reactive power compensation as demonstrated in Appendices 5.A and 7.A.

In the third model (Appendix 9.C) both STATCOM and UPFC PI controllers are configured by incorporating 3rd set of P & I values (P=0.38; I= 0.9 SP=400kV) to inject and absorb medium reactive power based on +/- 6% deviations. Based on this deviation the PI control model oscillated and took 24 iterations to stabilize the control loop by adjusting the medium reactive power compensation as demonstrated in Appendices 5.A and 7.A.

- **PI controller of Shunt converter:** The shunt converter is implemented to inject or absorb reactive power from the transmission line in between Bahrain and Qatar. There are two current components; one is real current to balance the real power of the series converter and other is reactive current to maintain the desired level of (capacitive and inductive) based on converter design capacity.

- **Reactive power compensation control mode of operations:** Based on capacitive and inductive reactive current requirement the PI controller is responding accordingly. The shunt converter adjusts the gating of the converter to minimize the reactive power deviation. The PI controller establishes the desired current based on VAR reference. In order to control the STATCOM precisely a closed loop feedback topology is employed. The Feedback signal will give the deviation against the reference value of the shunt converter to meet the required compensation in a time domain
- ***Voltage control mode:*** The shunt converter reactive current is maintained in order to control the transmission line voltage to a reference value at the connection point by using closed loop PI controller. This variation implemented based on droop characteristics of the controller.
- **Shunt and Series converter compensation by using PI controller:** In this control topology, the UPFC device has the capacity and the capability to operate independently or jointly. In an independent mode of operations the Capacitor bank has to split at a common DC bus link. In this mode of operation both devices will operate standalone with the same features as described in the last section. As per UPFC control mode of operations, the PI control technique is used to maintain voltage magnitude and angle of voltage vector at the desired operating condition in between the Kingdom of Saudi Arabia and Kuwait. This leads to control the line current vector more precisely to transfer desired reactive and real power transfer from the transmission lines without any constraints. The UPF control device is also providing solutions to control various time-based operational contingencies of the power transmission line at different operating conditions.

4.5.2. SSSC distributed PI control:

A PI control model's detailed calculations are performed and mathematical models developed and synthesized by incorporating a new set of PI configuration values as demonstrated in Appendix 6.A in order to control the 220kV line voltage of the AC system in between the UAE and Oman on the GCC power network. In the first model (Appendix 9.D) the SSSC PI controller is configured by incorporating the first set of P & I values(P=0.32; I= 0.6 and SP=220kV) to inject and absorb minimum reactive power +/- (CC2/LC2) based on +/- 2% deviations. Based on this deviation the PI control model oscillated and took 20 iterations to stabilize the control loop by adjusting the minimum reactive power compensation as demonstrated in Appendices 6.A.

In the second model (Appendix 9.E) the SSSC PI controller is configured by incorporating a 2nd set of P & I values (P=0.36; I= 0.8 SP=220kV) to inject and absorb medium reactive power based on +/- 4% deviations. Based on this deviation the PI control model oscillated and took 19 iterations to stabilize the control loop by adjusting the medium reactive power compensation as demonstrated in Appendices 6.A. In the third model (Appendix 9.F) the SSSC PI controller is configured by incorporating a 3rd set of P & I values (P=0.38; I= 0.9 SP=220kV) to inject and absorb medium reactive power based on +/- 6% deviations. Based on this deviation the PI control model oscillated and took 24 iterations to stabilize the control loop by adjusting the medium reactive power compensation as demonstrated in Appendices 6.A**.**

On-time domain simulation results are very much encouraging and validating the PI controller robustness. Based on these results and effective integration, a multiple portal of the controller has been developed and synthesized which is leading to run all three devices in parallel or independently to overcome any type of power transmission line contingences at different locations on the GCC power network as demonstrated in Appendix 9.D. These models are developed based on worst case scenarios to investigate most optimum PI control parameters to manipulate and adjust reactive power compensation as per defined three control limits, but in the real world these models will demonstrate different operating and control boundaries based on voltage and power deviation on the sending and receiving ends of the AC power system. In the first case if the deviation is larger than the controller, needs big step size to inject or absorb reactive power to minimize the deviation and stabilize the control loop. In the second case, if the deviation is smaller than the controller it will take a small step size to inject and absorb reactive power to minimize the deviation at the AC power system. By dividing and distributing the PI controller operating and control ranges into three small limits this will provide tangible and ultimate control on reactive power compensation with small step size without any constraints. This will also lead to make the controller response considerably faster**.**

- **PI Controller of Series Converter:**

Principally the series converter injects the voltage in series with in-line to maintain voltage magnitude and angle of the voltage vector in between Oman and the United Arab Emirates. In fact voltage injections in the line directly or indirectly control the power flow through the transmission line. Closed loop control topology is implemented to maintain required voltage injection and angle of the voltage vector more tangible to achieve the desired results. However, the results indicate that this approach has a great potential to enhance controller dynamic performance at a minimum cost and time, and it may stabilize the control loop within 10-15 iteration (iterations?). This is an instrumental concept to address a wide range of power system stability issues and control integration without any additional control support on the GCC power network.

4.6. Observations:

In this study a PI controller is implemented to control and optimize FACTS control devices at different locations on the GCC power grid. Figure 4-19 shows the responses of three models at different P and I values. The first waveform (blue trace) indicates that the control loop stabilizes after 21 iterations and this model is configured by integrating the following values P=0.32; I= 0.6 and SP=400kV. In the second waveform (magenta trace) this indicates that the control loop stabilizes after 19 iterations and this model is configured by integrating the following values of P=0.36; I= 0.8 SP=400kV. In the third waveform (yellow trace) this indicates that the control loop stabilizes after 24 iterations and this model is configured by integrating the following values P=0.38; I= 0.9 SP=400kV. These three PI control model's operating and control limits are integrated within STATCOM, & UPFC's +/- 2%, +/-4% and +/- 6% operating and control boundaries to manipulate and adjust their inductive and capacitive modes of operations at minimum, medium and maximum operating ranges as demonstrated in Appendices 5.A & 7.A.

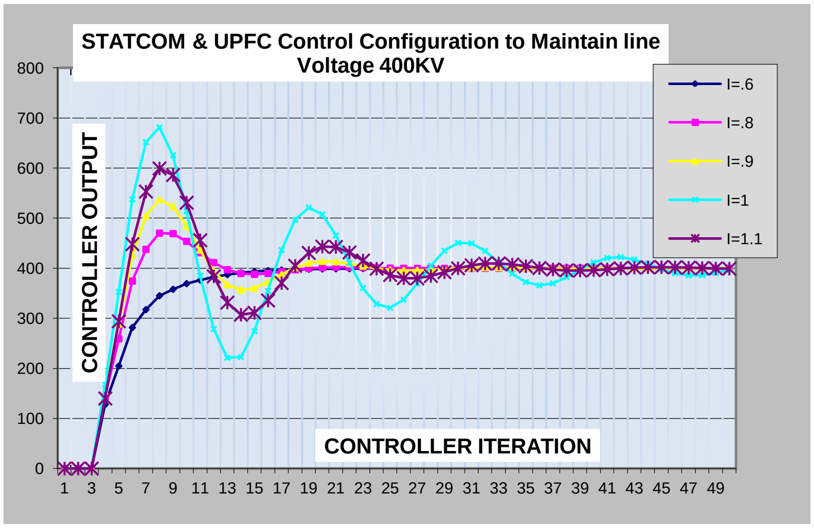


Figure 4-19: STATCOM and UPFC control schematic parameters

Figure 4-20 shows the responses of three models at different P and I values. In the first waveform (blue trace) this indicates that the control loop stabilizes after 20 iterations and this model is configured by integrating the following values P=0.32; I= 0.6 and SP=220kV. In the second waveform (magenta trace) this indicates that the control loop stabilizes after 19 iterations and this model is configured by integrating the following values P=0.36; I= 0.8 SP=220kV. In the third waveform this indicates that the control loop stabilizes after 18 iterations and this is model configured by integrating the following values P=0.38; I= 0.9 SP=220kV. These three PI control model's operating and control limits are integrated within SSSC's +/- 6% operating and control boundaries to manipulate and adjust their inductive and capacitive modes of operations at minimum, medium and maximum operating ranges as demonstrated in an Appendix 6.A.

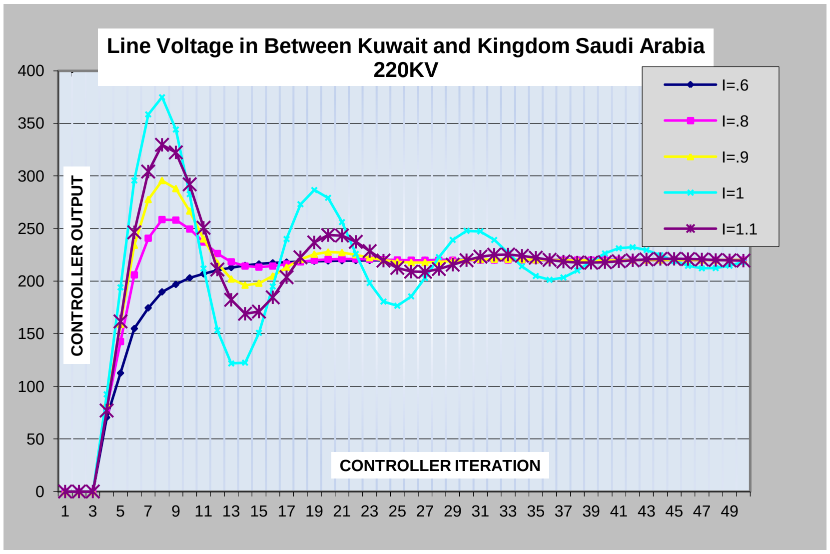


Figure 4-20: SSSC control schematic parameters

4.7. Results and Discussion:

After the implementing of these control models control values in Chapter 10 very promising results are obtained. Firstly, the FACTS devices operations and control parameters are synthesized individually to determine each device response independently based on control deviation. This is called the de-centralized control system topology. In the second phase, all FACTS devices are integrated to share the operational load and control systems automatically as per capacity and defined control limitations. This is also known as centralized control system topology. Based on our findings, it has observed that PI control technique played a vital and vigorous role to manipulate FACTS devices control and operations independently and jointly in order to meet growing operational requirements on the GCC power grid.

4.8. Summary:

The principal drive of this research work is to formulate a pragmatic approach in order to fine-tune and optimize FACTS devices time-based operations and control at different locations on the GCC power grid. In fact, constant and variable controls parameters are adjusted to manipulate FACTS devices operations in multi-dimensions to serve the purpose more convincingly. The control loops simulation and mathematical derived results indicate that a lot of improvements have been witnessed of the FACTS devices operations and control. In this chapter PID and PI controllers' response(s) are discussed. To enhance these controller responses various tuning methodologies viabilities are explained. By using *Douglas J. Cooper's* PID controller optimization technique optimum tuning parameters are selected and mathematically simulated. These simulation results are illustrated in appendices 4.A, 4.B, 4.C, 4.D, 4.E and 4.F. These results indicate effectiveness of tuning parameters to adjust the FACTS devices time-domain response based on operating parameters deviation (line voltage impedance and phase angle). Based on these tuning parameters, three control limits are designed for each FACTS device to inject or absorb reactive power compensation as per electrical power system operational requirements on the GCC power grid. These control limits with corresponding PI values are demonstrated in appendices 5.A, 6.A, and 7.A.

CHAPTER 5

The STATCOM connection between Qatar and Bahrain within the GCC interconnection

5.1. Introduction:-

This research work presents a nontraditional control and operation of a STATCOM connecting Qatar and Bahrain in the Gulf Cooperative Council Interconnection. A new optimization technique has been adopted to optimize the various process control parameters that contribute notably to control STATCOM device operations in a power system network during any undesired condition. This work will also demonstrate precisely STATCOM control parameters, improving the STATCOM performance at different transmission contingencies. The simulation is performed by taking into account STATCOM operating and control parameters; hereby the STATCOM controller is configured in a strategic way to optimize the control model by adjusting control and operating parameters precisely under both a steady and a dynamic state. The optimization process results are clearly indicating that the introduction of the STATCOM device in the right location of the system increases the loadability, reduces the losses and enhances the sustainability of the power system performance through optimization process. The new STATCOM control optimization technique can thus be effectively used for this type of optimization process. The GCC region has become a hub of major economic growth in the world. It is providing financial support and incentives to the GCC countries. Hereby, it has witnessed population growth and large scale industrial activities in the GCC countries. This has led to increased demand for electricity. Based on various analyses, we determined that the current demand for the GCC power consumption is about 60 GW and it is projected that it will reach 180 GW within next 25 years. In order to maintain a reliable, sustainable, and well-controlled power transfer between the GCC countries, it has been decided to interconnect the GCC countries. The interconnection is divided into two basic segmental links, neighboring to neighboring and common-link topologies. Firstly, Oman and The United Arab Emirates are interconnected through neighbor-to-neighbor control topologies. Secondly, Qatar, Bahrain, Saudi Arabia and Kuwait are interconnected through common-link control topology and this is also known as the Northern System. In the third stage common-link topology demonstrates UAE national grid and Oman northern grid interconnection; this is known as southern systems. Thirdly, southern and northern power systems are connected through hybrid link control topology. However, to improve these interconnected topologies, a large numbers of studies have been conducted to determine the technical and economical viability of the interconnection. The studies also demonstrate areas that require additional control devices. FACTS controllers are, therefore, strong candidates as technology options. Applications of FACTS controllers will deliver the following benefits [1], [2].

i) Increased power transfer capability in the GCC power grid.

ii) Increased power transfer capability

iii) Improved GCC power grid operational reliability

iv) Improved GCC power grid controllability

Figure 5-1 illustrates the designed power exchange and operational location of the STATCOM device in between GCC countries and Figure 5-2 shows an inter-tie connection with proposed STATCOM device in between Qatar and Bahrain on the GCC power grid. Figure 5-3 indicates the Matlab control model which demonstrates the simulation results. Prime contributions of this research work are as listed below.

i) Investigate the STATCOM impact on GCC power grid by implementing new optimization control technique.

ii) Compare the GCC Power grid system operations with and without STATCOM.

After the successful implementation of the STATCOM device, it will enhance the network loadability and voltage profile. The rest of this research study is structured as follows. After the introduction section, the GCC power system background, system reinforcement plan, FACTS device selection process, STATCOM Model description are described in Sections 5.2, 5.3, 5.4, and 5.5. The STATCOM model's optimized dynamic performance, observations and conclusion/results are described in sections 5.6, 5.7 and 5.8.

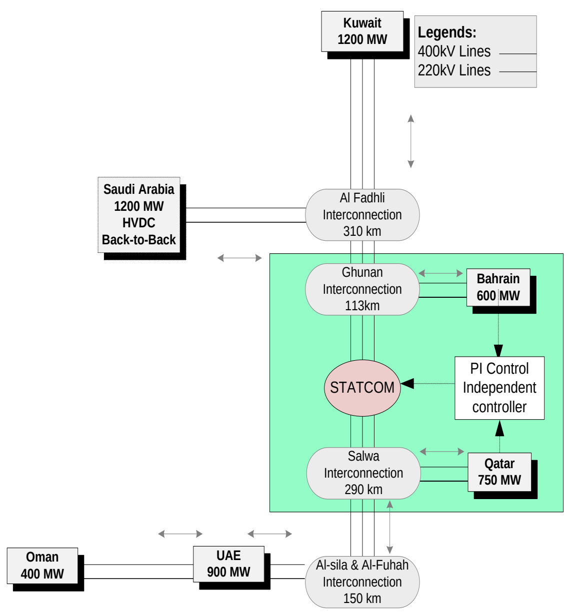


Figure 5-1: Simplified STATCOM control schematic to share and control 750MW at the Qatar side and 600 MW at the Bahrain Side

5.1.1 GCC Power system background information:

The GCC grid is configured and implemented into eight strategic power system operational directions in order to meet reliable and sustainable industrial and domestic customers' requirements on the GCC Power network as shown in Figure 5-2. The system that was considered firstly was a double-circuit

400 kV, 50 Hz line stretching from Al Zour substation (Kuwait) to Ghunan substation into (Saudi Arabia) with an intermediate connection at Fadhili (Saudi Arabia) and its associated substations. Secondly, a back-to-back HVDC link was introduced as a 380 kV interconnection, 60 Hz, system at Fadhili into Saudi Arabia in order to develop proper synchronization or communication with other GCC power systems, which are 50Hz frequency. Thirdly, a double circuit 400 kV overhead line stretching and partially connected with a submarine link from Ghunan substation to Al Jasra substation in Bahrain along with its associated substations. Fourthly, a double circuit 400 kV line stretching from Ghunan substation to Salwa substation into Saudi Arabia along with its associated substations. Fifthly, a double circuit 400 kV line stretching from Salwa substation to Doha South substation into Qatar and its associated substations. Sixthly, a double circuit 400 kV, 50 Hz line stretching from Salwa substation to Ghuwaifat substation in the United Arab Emirates along with its associated substations. Seventhly, a double and a single circuit 220 kV,50Hz line stretching from Al Ouhah united Arab Emirates to Al Wasset substation in Oman along with its associated substations; finally, a centralized control room was established at Ghunan in Saudi Arabia in order to control power system operations within all GCC countries with a certain degree of precision at different voltage and shared power perspectives [4],[5].

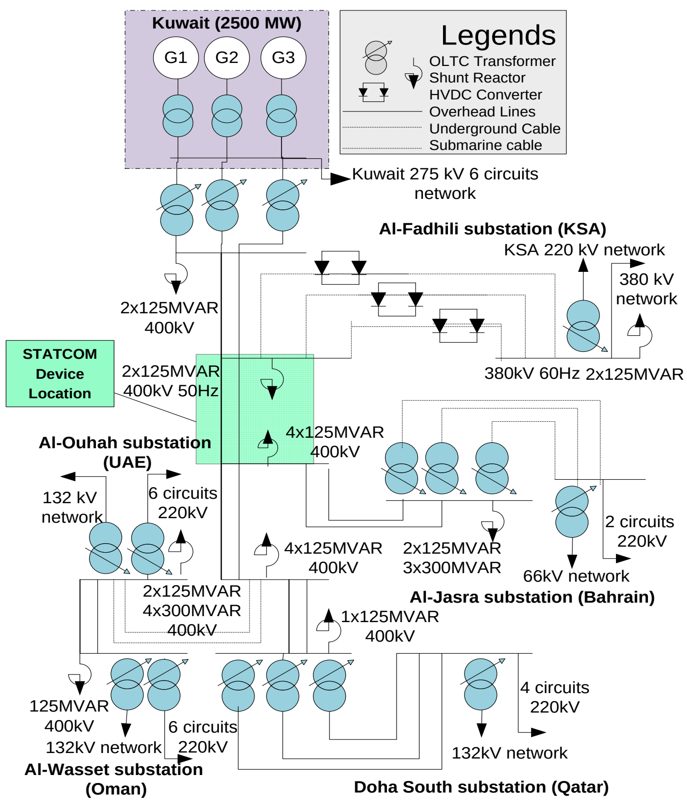


Figure 5-2: Proposed area (shaded) for the STATCOM implementation in between Qatar and Bahrain

5.1.2. STATCOM Mathematical Model

Figure 5-3 indicates the simulated model of the STATCOM device. The STATCOM is a voltage-sourced-converter (VSC)-based shunt-connected device on the GCC power grid. This device is injecting a current of variable magnitude in quadrature with the line voltage. Primary aim of this device to inject and absorb reactive power based on required transmission line compensation [9]. An equivalent circuit for the STATCOM is shown in Figure 5-2. The loop equations for the circuit may be written in vector form as.

$$\frac{d}{dt} i_{abc} = \frac{R_s}{L_s} i_{abc} + \frac{1}{L_s}(E_{abc} - V_{abc}) \qquad (5.1)$$

Where Rs and Ls represented the STATCOM transformer losses, E_{abc} presents the inverter ac side's phase voltage, V_{abc} presents the power system-side phase voltages, and i_{abc} presents the phase currents. The STATCOM output is denoted in equation 5.2.

$$E_a = kV_{dc}\cos(\omega t + \alpha) \qquad (5.2)$$

Where V_{dc} is the voltage across the dc capacitor, k is the modulation gain, and α is the injected voltage phase angle. By defining a proper synchronous reference frame, the dynamic model can be simplified[9]. The reference frame coordinate is defined in which the d- axis is always coincident with the instantaneous system voltage vector and the q-axis is in quadrature with it. By transforming the system model to this reference frame, the STATCOM equations at bus 1 can be written as

$$\frac{1}{\omega_s}\frac{d}{dt} i_d = -\frac{R_s}{L_s} i_d + \frac{\omega}{\omega_s} i_q + \frac{k}{l_s}\cos(\alpha + \theta_i)\, V_{dc} - \frac{V_i}{L_s} sin\theta_i \qquad (5.3)$$

$$\frac{1}{\omega_s}\frac{d}{dt} i_q = -\frac{R_s}{L_s} - \frac{\omega}{\omega_s} i_d + \frac{k}{l_s}\sin(\alpha + \theta_i)\, V_{dc} - \frac{V_i}{L_s} sin\theta_i \qquad (5.4)$$

$$\frac{C_{dc}}{\omega_s}\frac{d}{dt} V_{dc} = -k\sin(\alpha + \theta_i)\, i_d - ksin(\alpha + \theta_i) i_q - \frac{V_{dc}}{R_{dc}} \qquad (5.5)$$

Where i_d and i_q are injected d_q STATCOM currents, V_{dc} is the voltage across the dc capacitor, R_{dc} represents the switching losses, R_s and L_s are the coupling transformer resistance and inductance, respectively, and the STATCOM rms bus voltage is $V_i\angle\theta_i$. The power balance equations at the STATCOM bus are

$$0 = V_i\left(i_d cos\theta_i + i_q sin\theta_i\right) - V\sum_{j=1}^{n} V_j Y_{ij}\cos(\theta_i + \theta_j - \emptyset_{ij}) \qquad (5.6)$$

$$0 = V_i\left(i_d sin\theta_i + i_q sin\theta_i\right) - V\sum_{j=1}^{n} V_j Y_{ij}\cos(\theta_i + \theta_j - \emptyset_{ij}) \qquad (5.7)$$

Where the summation terms represent the power flow equations, $Y_{ij}\angle\phi_{ij}$ is the *(i, j)* element of the admittance matrix, and 'n' is the number of buses in the system. The first set of terms indicates the active and reactive powers injected by the STATCOM. The control objective for the STATCOM is to provide independent reactive power support and to maintain constant dc capacitor voltage. This is the best accomplished by regulating the PWM switching commands to alter the modulation index and phase angle. The input signals V_{dc} and Q are compared against reference values and used to compute the error signals in i_d & i_q. A PI-based control is then used to produce the controls signals k.

In reality, both the firing angle α and modulation gain k are impacted by the changes in i_d & i_q. However, since α is more strongly correlated to changes in i_q and k is more strongly correlated to changes in i_d, the cross coupling terms can be neglected $(K_d = k_q = 0)$ leading to a decoupled control approach[8],[9].

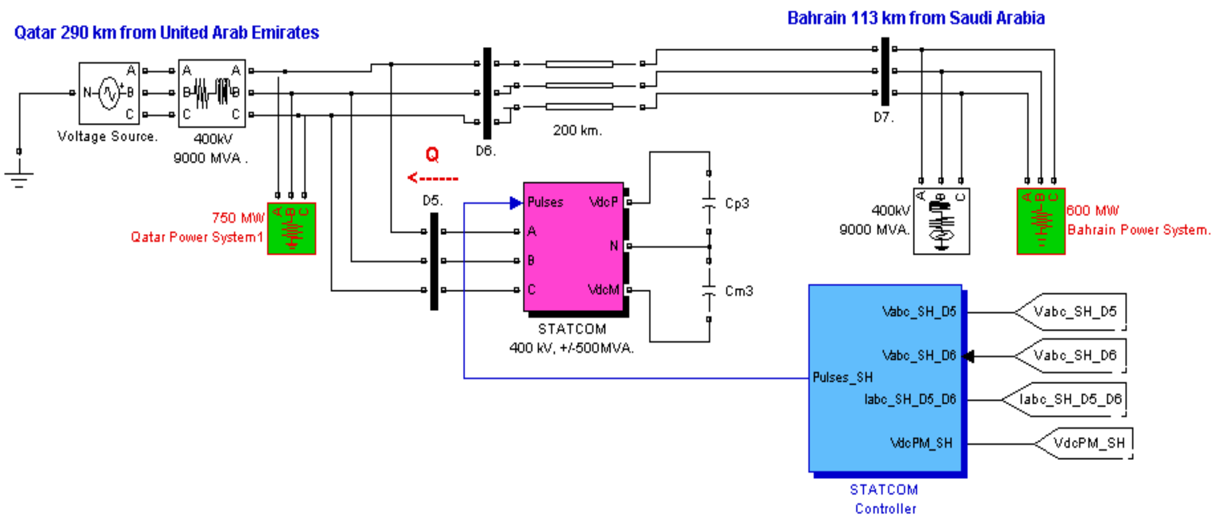


Figure 5-3: STATCOM control schematic in between Qatar and Bahrain [Matlab]

5.1.3. Power system reinforcement plan in between the Qatar and Bahrain:

Various analyses were carried out to identify and determine the system requirements at both ends of transmission system. In this study, the Qatar substation site is selected for the STATCOM installation for the following reasons: The first strategic approach as defined in Figure 5-3 is based on the fact that Bahrain and Qatar have an interconnection with industrial and domestic consumers at Doha South substation (Qatar) and Al-Jasra Substation (Bahrain). Further investigation identified that some power system oscillations may exist on their systems, and consequently, also on the consumers' side of the system. This effectively means that in between the Qatar and Bahrain locations, there is an opportunity to utilize the ability of the STATCOM to damp all types of existing and potential future oscillations. The second strategic approach also defined in Figure 5-3 is based on the fact that the main transmission line coming out from KSA and Kuwait 400kV bus is exposed to an increase in voltage levels during light load conditions due to the inherent shunt capacitance of the 400kV transmission line. Likewise, the 220kV bus is exposed to a reduction in voltage levels during peak load conditions on both sides of Bahrain and Qatar. The Doha South substation (Qatar) and Al-Jasra Substation (Bahrain) sites are the best locations on the Qatar and Bahrain network where the total symmetrical range of the reactive output from the STATCOM, from full inductive to full capacitive, could be utilized without applying fixed capacitors [4], [5].

5.1.4. STATCOM model's distributed control:

Appendix 5.A introduced and demonstrated the STATCOM control model's three distributed control limits which are designed to maintain minimum +/-2% medium +/-4%, and maximum +/-6% against the corresponding deviation of each control limit. These deviations are compensated at three operating limits by adjusting STATCOM control device with corresponding P & I control values as stated in Appendix 5.A Table. The STATCOM control device oscillates based on corresponding P & I value of each limit in between +/-2% +/-4% and +/-6% deviations at both sides (receiving and sending ends) of transmission lines to adjust reactive power compensation. These control boundaries are customized and synthesized by providing P &I configuration values. These values are enabling the control system to communicate each limit accurately and adjust the reactive power compensation respectively at defined locations on the GCC power grid. These control boundaries will effectively operate when more than one FACTS device will be in operations at different location on the GCC power grid. These will also communicate to each other based on voltage, impedance, angle and power flow deviation at sending and receiving ends of the Qatar and Bahrain power system facilities [6], [7].

5.2. STATCOM controller's selection process (WDB)

The estimated values are providing a positive indicator to understand how long and what resources are needed to assess the credibility of the FACTS controllers on the GCC power grid. In this study a Wideband Delphi technique has been used to evaluate various experts input from Academia and Industry. This is a simple iteration technique which is used to establish each segment estimated value as demonstrated in Table 5.1. Based on WBD technique 12 essential areas of FACTS devices have been selected to identify and determine the operational and control reliability as well as feasibility on the GCC power grid [14].

TABLE 5.1: STATCOM DEVICE CRITERIA SIGNIFICANCE

S.No	Criteria	Weight (%)	S.No	Criteria	Weight (%)
1	Control Significance	15	7	Refuse disposal	5
2	Control Integration	10	8	Monitoring equipment	5
3	Design Capacity	5	9	Simulation results	5
4	Reliability	10	10	Capex	10
5	Maintenance frequency	15	11	Opex	10
6	Availability for field trial	5	12	Post Installation Support	5
			Total		100

These essential areas are (i) control significance: *FACTS devices have a robust control to meet the desired compensation of the power system network within a few cycles on the GCC power grid*. (ii) Control integration: *FACTS device has the capacity and capability to communicate and maintain parallel operations with other devices on the GCC power grid*. (iii) FACTS devices design capacity: *based on their design capability how much each device can manage the reactive power compensation* *based on active power transfer load*. (iv) FACTS devices operational reliability: *How effectively each device can run the operations without any possible downtime*. (v) Maintenance frequency: *less maintenance frequency will reduce the operating costs considerably of the power network*. (vi) Availability for field trial: *To evaluate device operation and control in the real-world*. (vii) Refusal disposal: *No disposal during installation and normal operations*. (viii)Monitoring equipment: *these are the indicators to measure the performance during the trial*. (ix) Simulation results: *these are obtained by using Matlab engineering software to take decisions. (x)* Capex: capital expenditure which comprises feasibility study, FEED, installation, pre commissioning and commission cost. (xi) Opex: operating and management expenditure. (xii) Post installation support: *this is a mandatory aspect to provide maintenance and technical support during operations.* In the beginning stage this is the core responsibility of the WBD originator to structure a team that includes between five and seven competent members. These members will participate in the meeting and brainstorming assumptions as well as deciding the unit for the estimation process. After the first meeting each member will prepare an individual report by incorporating missing assumptions or estimations in case there is a very wide variation in the estimated values. In order to reduce the deviation this is very important to repeat numerous estimation sessions to establish and develop consensus on different experts' opinions as demonstrated in Figure 5-4 until the required values are obtained at very narrow variation. Figure 5-5 indicates the wide variation in the first estimation session and it was reduced in the second and narrow in the third estimation session [14].

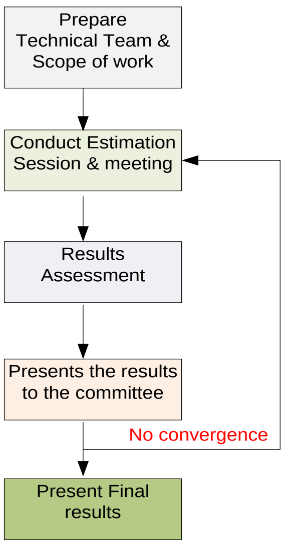


Figure 5-4: Wideband Delphi Process Flow Diagram

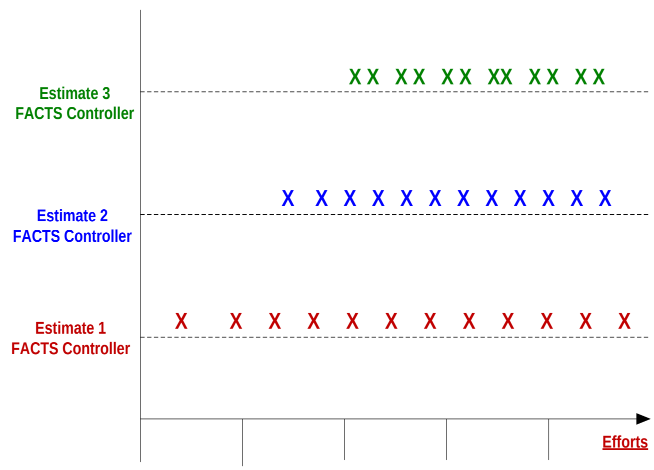


Figure 5-5: Wideband Delphi repeated process

After getting proper convergence as mapped in the Figure 5-4 the final results of each segment must be compiled and presented as a final task to the technical committee for approval and implementation successfully. The steps mentioned below ought to adhere to perform the Wideband Delphi Technique process framework.

1. A form was developed by integrating all 12th areas and their specification and corresponding estimated score.
2. This form was sent to each defined expert individually to receive his/her composite input theoretically and practically.
3. In the third step a meeting was called to develop consensus on provided estimated scores of each area.
4. After the meeting one more form is provided to the expert individually to fill out anonymously without sharing with anyone.
5. After receiving their input a summary was prepared and distributed to the expert to have their further input if any.
6. In the sixth step one more meeting was called, specifically to understand the expert opinion that is having a very wide variation on the estimated score.
7. After thorough discussion and developing consensus, again one more form is provided to the committee members to fill out anonymously. Step 5 to seven can be repeated as many as appropriate in order to obtain a seamless estimated score.

5.2.1. Criteria Significance WBD:

Table 5.2 demonstrates the aggregate score of significance which is comprised of five sections. The first section is carrying a zero score against no submission or no consequences. The second section is carrying 20 marks against the some submission or unacceptable low. The third section is carrying 50 marks against the satisfactory submission. The fourth section is carrying 65 marks against the good submission. The fifth section is carrying 80 marks against the significant submission above the minimum or strong candidate. In the last section this is carrying 100 marks against the exceptional submission. These scores are the reference value to select any device.

TABLE 5.2: STATCOM DEVICE SUBMISSION CRITERIA SCOREBOARD

Criteria Description	:	Submission Score
No submission of any consequence	:	0
Some submission but unacceptably low	:	20
Satisfactory	:	50
Good submission	:	65
Significantly above the minimum acceptable. Considered a strong candidate.	:	80
Exceptional submission	:	100

5.2.2. Assessment criteria:

Table 5.3 indicates the stringent estimated score of each FACTS control device. These scores are derived from Table 5.1 and 5.2 by using the equation (5.8) as explained below. These assumptions and estimations are assessed against the maximum and minimum values of each segment of each device. However the evaluation process was repeated to minimize or eliminate wide variation, if persisting, in order to obtain seamless figures.

TABLE 5.3: STATCOM DEVICE ESTIMATED SCORE

Device	Submission Score	Device	Submission Score
TCVR	45	STATCOM	76
TCPAR	50	SVC	56
UPFC	65	GCSC	40
IPFC	60	TSSC	37
SSSC	65	TCSC	42

5.2.3. Results review and final decision:

After successful calculation and estimation the aggregate values of all FACTS devices are demonstrated in Table 5.5 & 5.6 indicates the individual FACTS device calculation scores by using the equation (5.8) as indicated in Table 5.4. If the summation score of any device is above 65 it means good submission and 80 significant (strong candidate). The results indicate that STATCOM device is a strong candidate to be implemented in between Qatar and Bahrain on the GCC power grid. Therefore, the Wideband Delphi technique has given very prolific supporting results in order to formulate the selection process of FACTS devices more pragmatically [14].

$$CRV_Z = \sum_{n=1}^{12} \frac{B_n}{100} xCn = \left(\frac{B_1}{100} xC1 + \frac{B_2}{100} xC2 + \frac{B_3}{100} xC3 \ldots. + \frac{B_{12}}{100} xC12\right) \quad (5.8)$$

Where:
Z(subscript) STATCOM, SSSC, UPFC, …..etc
$CRV_{STATCOM}$ (credible value)
B_1 to B_{12} (Significant criteria as per Table 5.1)
C1 to C12 (Constant value of each device as shown in Table 5.2)

This equation comprises of 12^{th} section corresponding to Table 5.1 as an input data from B1 to B12 this is also called the nominator and first part of the equation (5.8). These 12 areas total output value must be equal to 100. This is also called the denominator and second part of the equation (5.8). Third part of the equation is “C_1 to C12” this is submission value of each segment of 12 areas as demonstrated into Table 5.2. During the calculation process the numerator is divided by the denominator and multiple with “C1 to C12” values in order to get final value of the each segment as indicated in Table 5.4.

TABLE 5.4: CALCULATED SCORE BY USING EQUATION 5.8

Criteria	$B_{1...12}$	$C_{1...12}$	Equation (5.8)	Weighted Score
Control Significance	15	70	$(B_1/100).C_1$	10.5
Control Integration	10	70	$(B_2/100).C_2$	7
Design Capacity	5	80	$(B_3/100).C_3$	4
Reliability	10	70	$(B_4/100).C_4$	7
Maintenance frequency	15	70	$(B_5/100).C_5$	10.5
Availability for trial	5	70	$(B_6/100).C_6$	3.5
Refuse disposal	15	23	$(B_7/100).C_7$	3.5
Monitoring equipment	10	55	$(B_8/100).C_8$	5.5
Simulation results	5	100	$(B_9/100).C_9$	5
Capex	10	80	$(B_{10}/100).C_{10}$	8
Opex	15	53	$(B_{11}/100).C_{11}$	8
Post Installation Support	5	70	$(B_{12}/100).C_{12}$	3.5
Total	100	-	-	76

TABLE 5.5: STATCOM DEVICE CALCULATED SCORE AGAINST OTHER DEVICES

Static Shunt Compensator			**Static Series Compensator**		
STATCOM		SVC	GCSC	TSSC	SSSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	10.5	8.4	6	9.8	9.8
2	7	5.6	4	6.5	6.5
3	4	3	2	3.3	3.3
4	7	5.6	4	6.5	6.5
5	10.5	8.4	6	9.8	9.8
6	3.5	3	2.5	4	4
7	3.5	3	2.5	4	4
8	5.5	3	4	4	4
9	5	3	3	3.8	4
10	8	6	5	6.5	6.5
11	8	6	5	6.5	6.5
12	3.5	3	4	3.3	4.5
Total	76.00	58.00	46.00	68.0	69.0

TABLE 5.6: STATCOM DEVICE CALCULATED SCORE AGAINST OTHER DEVICES

Static voltage and phase Angle control			**Combined Compensator**		**Static Series Compensator**
TCVR		TCPAR	UPFC	IPFC	TCSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	6.75	7.5	9.75	9	6.3
2	4.5	5	6.5	6	4.2
3	2.25	3.5	4	4.5	2.1
4	4.5	5	6.5	6	4.2
5	6.75	7.5	9.75	9	6.3
6	2.25	3.5	3.25	5.5	5.1
7	3	4.5	5.25	4	2.1
8	3	3.5	4	4	5.1
9	3	3.5	4	4	2.2
10	4	5	6.5	6	4.2
11	5	5	6.5	6	4.2
12	3	3.5	3	5	3
Total	48.00	57.00	69.00	69.00	49

5.2.4. Estimation Principal rules

- It is very important to understand the form must be filled individually without any pair or group interaction. The originator must ensure that every participant partially does not skew the results.

- The originator (estimator) must neglect any external influence factor, the principal objective is to develop consensus between the technical team members on realistic values rather than what the originator wants to hear.
- The originator must indicate the characteristic that influences their values; this will help to build a transparent worksheet.
- The originator must define the time limit, this will help focus, and continuity and progress.

5.2.5. Wideband Delphi Strengths

This is a very simple technique that does not require estimation experts. This process is very composite and prolific so everyone can participate actively in the assigned responsibilities. The estimated values are produced based on strong consensus through a number of iteration sessions. This will help to eliminate individual error if they persist. The expert comparative judgment will provide an effective driving force to produce high quality results [14].

5.2.6. Wideband Delphi Weaknesses

The originator must be strong technical and managerially. This is very important to determine the competence of the participants.

5.2.7. WBD and GA technique comparative analysis

WBD technique has unlimited capability and capacity to incorporate multiple parameters as input for the evaluation purpose. It will produce high quality results satisfactory based on input data being used. GA is also called the ranked based selection process to evaluate various selection process parameters based on reservation and grouping calculation. It will produce the results satisfactorily no matter what input signal is being used during the grouping calculation process. GA uses time-based parameters to evaluate system performance e.g. processing time, setup time and study handling time etc. *Conclusively, the WDB technique is a prolific approach comparatively GA to determine seamless selection process. This technique may be used for other purposes as well [18], [19].*

5.3. STATCOM model's case study (Qatar & Bahrain):

Table 5.7, 5.8 and 5.9 demonstrate the STATCOM input data that is used to develop and simulate the STATCOM control model. A 500-Mvar STATCOM is implemented in between Qatar and Bahrain to regulate voltage on a three-bus 400kV in order to meet long transmission system operational requirements. Effectively, in normal operational conditions the STATCOM device adjusts the VSC (voltage source converter) output to maintain its voltage in phase with the AC system voltage in between the Qatar and Bahrain. The STATCOM device generates or absorbs the reactive power based on VSC (voltage source converter) output voltage. It is very important to understand the amount of reactive power based on converter output voltage magnitude and coupling transformer leakage reactance.

The slight change in voltage angle will allow a small amount of reactive power to flow to the DC bus in order to charge or discharge capacitor bank. Figure 5-6 & 5-7 indicate 1200 MW power delivered into the shared GCC Power grid. As per the graph below the transmission line voltage and reactive current are well controlled by implementing an optimized control technique with high degree of precision. During a simulation process it was observed that the reactive current was oscillating form 0.1 to 0.3 second to maintain reference reactive current to main certain level of voltage level. During the optimization process reactive power was dropped for 0.07 second and ramped up for 0.05 seconds. Momentarily, it was gradually dropped in order to maintain reference reactive power. To maintain STATCOM optimized operations, the thyristor firing angle is also in a tight controlled mode. Additionally, the thyristor firing angle also indicates a couple of alpha peaks momentarily during ramp up or ramp down to maintain reactive power compensation for the long transmission line [15].

TABLE 5.7: POWER, VOLTAGE AND FREQUENCY

Countries	Power Exchange, Voltage & Frequency
To the Qatar or from Qatar to main transmission line	750MW, 400kV, 50Hz
To the Bahrain or from Bahrain to main transmission line	600MW, 400kV, 50Hz

TABLE 5.8: EXISTING REACTIVE POWER AND DISTANCE

Existing Power System	Reactive Power	Distance
Reactive Power Demand at Al-Ghunan substation KSA	500MVAR	Al Fadhili substation (KSA) to Al-Ghunan Substation (KSA) =114 Km
Reactive Power Demand at Al Jasra substation Bahrain	850MVAR	Al-Ghunan Substation (KSA) to Slawa Substation (Qatar) = 288Km
Reactive Power demand at Al-Salwa Substation	500MVAR	Slawa Substation (Qatar) to Doha South Substation = 97Km
Reactive Power demand at Doha South Substation	250MVAR	

TABLE 5.9: MULTIVARIABLE CONTROLLER'S CONFIGURATION OF THE STATCOM

STATCOM LOCATION: Shunt connected at Salwa substation in between Bahrain and Doha	Iq regular: Kp 12dB; Ki: 0.015 dB	CC1 and LC1 = minimum compensation capacitive or inductive (VC voltage change from 1 to 2%)
Rated STATCOM: +/- 500 MVAR	Ref V: 1.0 pu (400kV)	CC11 and LC11 = medium compensation capacitive or inductive (VC voltage change from 2% to 4%)
P (proportional): 0.32, 0.36, 0.38, 0.42 I (integral) 0.6, 0.8, 0.9, 1.1 D (derivative): none	Droop: 0.033pu/100MVA; Kp:14dB; Ki: 3500dB	CC111 and LC111 = full compensation capacitive or inductive (VC voltage change from 4-6%)

5.3.1. STATCOM optimized dynamic response:

Figure 5-6 indicates voltage control mode of the STATCOM and it adjusts the converter voltage against the reference voltage (Vref=1.0). The controller's voltage droop of the regulator is maintained at 0.04pu/100VA. In normal operational conditions the STATCOM changes its operating point from capacitive to inductive (+/-500MVAR) mode of operations. The STATCOM converter output voltage varies between 1-0.025=0.97 pu and 1+0.025=1.035 pu. When the STATCOM is out of service and it has been observed that the SVC terminal voltage maintained at 1.0pu based on set voltage of SVC at 1.040pu. Initially the STATCOM is floating at zero current, in fact the Ref_ voltage is set to 1.0pu. The DC_voltage (Vdc) is 19.3kV at 0.15s voltage drastically dropped by 2.7% (0.981pu) of normal voltage at the AC system. Based on this deviation the SVC (voltage source converter) activates and generates reactive power (500Mvar) in maintaining the voltage at 0.985pu certain level to reduce the deviation. During this operation the Vdc increased accordingly. The voltage source converter voltage increased within 0.15s from 0.985 to 1.037pu of its normal voltage. Based on this deviation the SVC activates from capacitive to inductive mode of operations and absorb reactive power (500Mvar) in order to maintain the AC system voltage equal to reference value or 1.013pu.

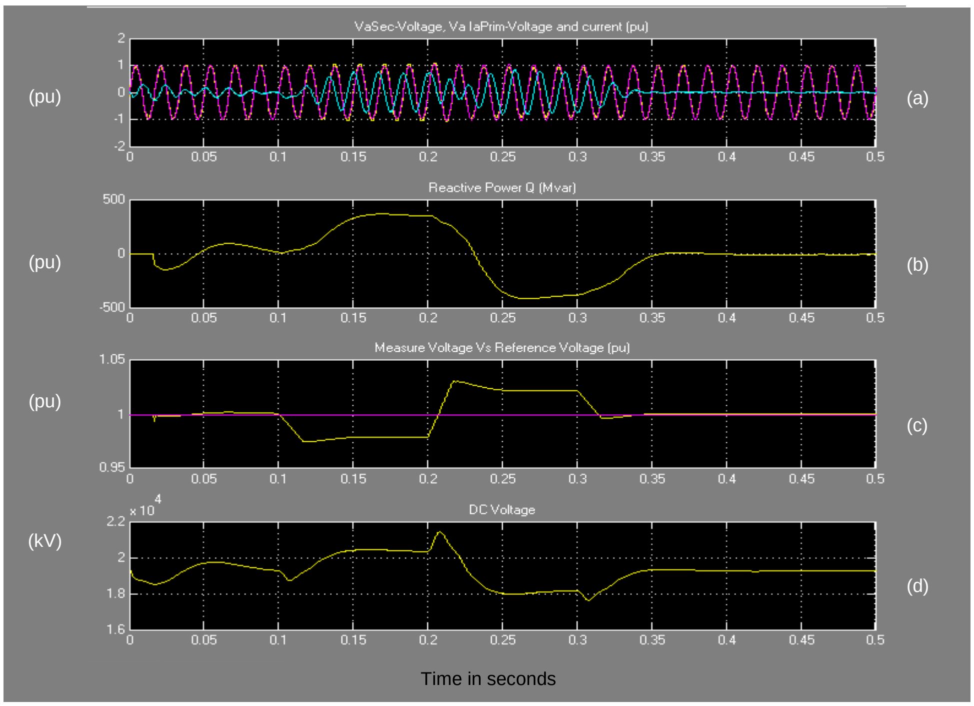


Figure 5-6: indicates STATCOM four waveforms (a) measured primary and secondary voltage (b) reactive power (c) measured and reference voltage (d) DC voltage

5.4. Observations:

Figure 5-7 is indicating the analysis of STATCOM key parameters, in first trace Vref and measured voltage variation from 1pu to 0.98pu and 1pu to 1.03pu is observed. In the second trace the variation in Iqref and Iq_ measure observed. It is noticed that the Iq _ measure oscillated from -1.8pu to 1.7pu on the same path of Iq_ reference and, it was leveled after 0.35 second. In the third trace, variation in PQ was observed, the Q value oscillated to compensate required reactive power as per defined boundary from -1pu to 1pu (+/- 500 Mvar). In the last trace the behavior of the alpha angle was observed, there was small oscillation from 0.05 to 0.1 seconds. To take a corrective action to minimize the error, all observations were addressed by adjusting the control parameters precisely by considering adequate safety and security margins. Figure 5-9 is indicating sending and receiving end voltages at both sides of the STATCOM, which was controlled precisely to optimize STATCOM operations in order to deliver sustainable and reliable 1200 MW power into the GCC Power grid [21].

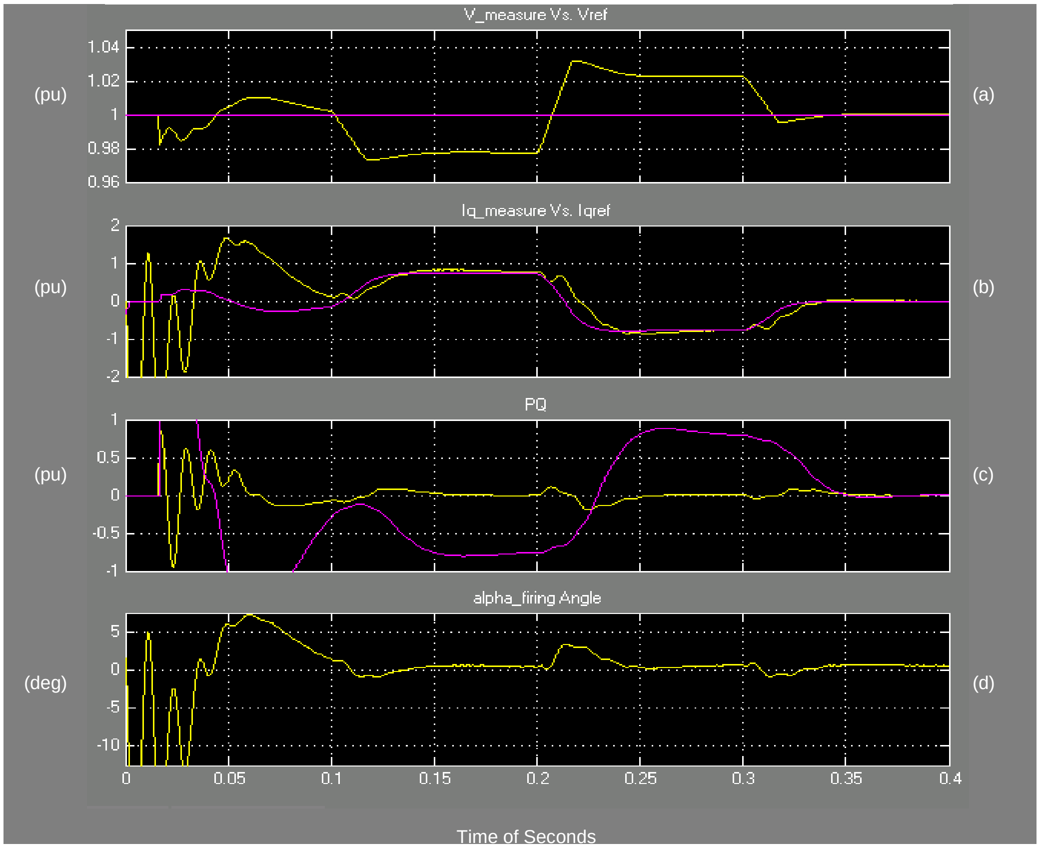


Figure 5-7: STATCOM Control parameters (a) measured and reference voltage (b) Iq measured and Iq reference (c) measured real and reactive power (d) Alpha firing angle control

5.4.1. Effectiveness of the STATCOM control device

Figure 5-8 indicates the receiving and sending ends voltage without STATCOM at Bahrain and Qatar. Figure 5-9 shows the improved voltage with STATCOM at both the receiving and sending ends of Bahrain and Qatar. These results were obtained after implementation of PID new configuration control parameters. Figure 5-5 also demonstrates the STATCOM effectiveness as given below. In the first trace, the waveforms show Vref (magenta trace) and measured voltage (yellow trace) variation from 1pu to 0.98pu and 1pu to 1.03pu. In the second trace, the variations in Iqref (magenta trace) and Iq(yellow trace) waveforms are observed. It is noticed that the measured Iq _ oscillated from -1.8pu to 1.7pu on the same path of Iq_ reference and, it then leveled to a steady state value after 0.35 s. In the third trace, a variation in real and reactive powers P and Q are observed; the Q value oscillates to compensate the required reactive power as per defined boundary from -1pu to 1pu(+/- 500 Mvar). In the last trace, the behavior of alpha angle is observed; in this case, there is small oscillation from 0.05 to 0.1 s. In order to enforce a corrective action to minimize the error, all observations are addressed by adjusting the control parameters precisely by considering adequate safety and security margins [19], [20].

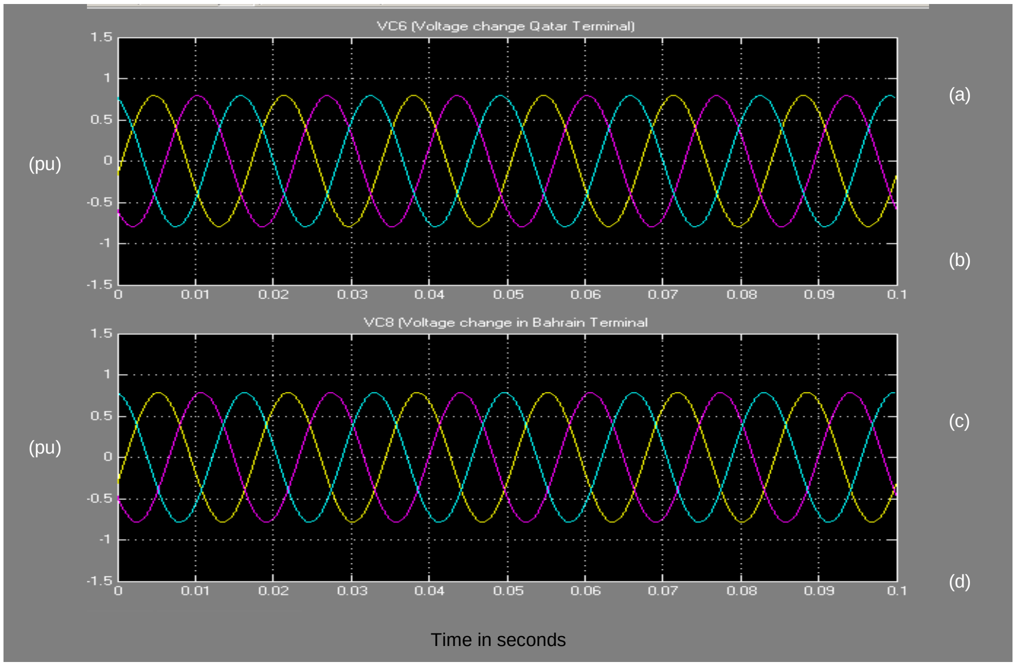


Figure 5-8: Receiving end voltages at both side of Bahrain and Qatar without STATCOM (a) receiving end voltage (b) sending end voltage

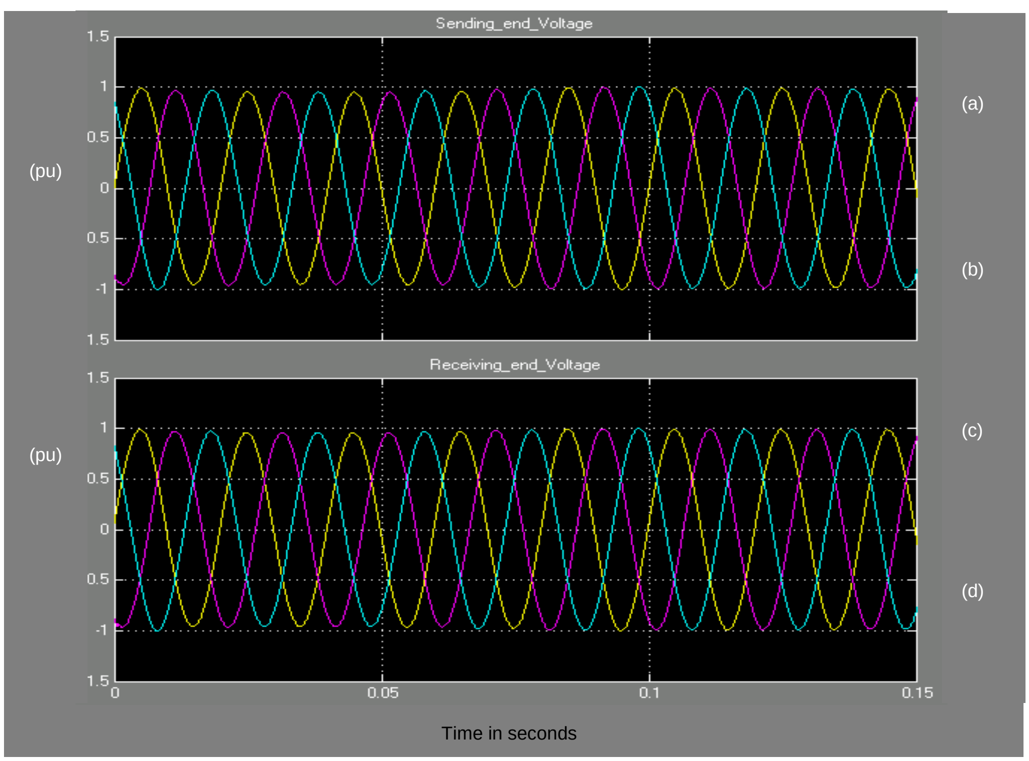


Figure 5-9: Receiving and sending ends improved voltages at both sides of Bahrain and Qatar with STATCOM (a) receiving end improved voltage (b) sending end improved voltage

5.5. Results and Discussion

The STATCOM control model has been developed into three distributed control limits which are defined to adjust reactive power: minimum, medium and maximum. This controller oscillates between +/- 2, 4 and 6% at both sides of transmission lines to adjust reactive power compensation as required. These control boundaries will communicate and adjust reactive power compensation based on sending and receiving ends voltage deviation. The controller will oscillate and inject or absorb controlled reactive power based on corresponding PI controller values of each operating boundary as demonstrated in Appendix 5.A. These control boundaries will effectively operate when more than one FACTS device will be in operation at different locations on the GCC power grid. These will communicate to each other based on voltage, impedance, angle and power deviation at sending and receiving ends. Based on the above discussion various investigations have been carried-out by introducing new control and tuning parameters further discussed in chapter no.9. A simulation technique validated and its results to share 600MW power on the Bahrain and 750MW on the Qatar network. In order to meet industrial and domestic loads operational requirements were establish at various operating conditions. The results also show that STATCOM is versatile equipment with outstanding dynamic capability to improve the voltage profile, power angle and stability margin in between Qatar and Bahrain. Based on these results, STATCOM is a very strong candidate to be implemented on the GCC power grid. It also exhibits a positive impact on neighboring countries' power system operations on the

5.6. Summary:

In this chapter, the STATCOM device model demonstrates its impact in between Qatar and Bahrain to improve power system's control and operations on the GCC power grid. After providing adequate compensation through the STATCOM device the Qatar power network will share 750MW power and the Bahrain power network will share 600MW without any restraint. Based on these improvements the GCC power grid has the capability and capacity to share 1200MW power from KSA and 1200MW power from Kuwait to meet industrial and domestic loads requirements at different atmospheric (summer/winter) operating conditions on the GCC power grid. Hereby the GCC power system background and viabilities are also addressed as well as the STATCOM reinforcement plan. In addition to that, the STATCOM model's new control optimization and device selection techniques are described in detail as well as its prompt application in order to resolve various control and operational issues precisely. Based on this control technique three control limits along with corresponding PI values are incorporated into the STATCOM model and simulated as demonstrated in appendix 5.A. These control techniques are providing a lot of confidence to operate the STATCOM device independently or jointly (integrated) as discussed in Chapter 9.

CHAPTER 6

The SSSC Connection between Oman and United Arab Emirates within the GCC Interconnection

6.1 Introduction:-

The proposed work is a novel design and controllability optimization technique which has been implemented prudently to simulate the SSSC control operations in order to identify and determine various control parameters which are contributing considerably to control the SSSC device operations in multiple directions in a power system network at different locations on the GCC power grid during any undesired conditions. In order to maximize utilization of the SSSC control device operations on the GCC power grid, hereby SSSC control parameters are reconfigured in different strategic ways to optimize the SSSC model performance by adjusting its control parameters more tangibly under both steady and dynamic states. Herein the SSSC device operational controllability results are clearly indicating that the introduction of SSSC device in between the Oman and United Arab Emirates network will reasonably enhance the power system loadability, diminish the losses and improve sustainability of the power system performance throughout the GCC power grid. Hereafter, new SSSC control device optimization techniques can thus be successfully used for this type of optimization process. This research work demonstrates prolific and composite simulated results; these are extracted after application of an SSSC control device with total rating +/-250MVAR in between Oman and The United Arab Emirates at optimum location no.3. The optimum location has been recognized and examined on the GCC power grid by carrying out a wide-range of complex power system studies and surveying. In order to control the SSSC operations at different location(s), a novel control technique was implemented to communicate with other FACTS devices within the GCC power grid, by considering operations and control system parameters' criticalities. A multi-variable controller was developed and synthesized by considering all control parameters at a micro level, which has the ability to communicate and control all FACTS devices (STATCOM, SSSC, and UPFC) which are in operation at different locations' time domains in the GCC power grid. Hence, an optimization technique was configured to recognize and assess each FACTS device(s) available to provide required compensation to enhance the over-all network performance, simultaneous with reducing the network losses. The GCC power grid encompassed four segments; i) the first segment demonstrates power system facilities in between Kuwait and Saudi Arabia, ii) the second segment demonstrates in between Qatar and Bahrain, electrical power facilities, iii) the third segment demonstrates in between Oman and United Arab Emirate, electrical power facilities and iv) the fourth segment focuses on the HVDC link to synchronize the Kingdom of Saudi Arabia to the entire GCC power grid due to it 60Hz frequency (Note that all GCC countries Power system is operating at 50 Hz frequency except the kingdom of Saudi Arabia) Herein, Figure 6-1 illustrates the designed power exchange between GCC countries and Figure 6-2 illustrates an inter-tie connection in between the GCC countries and their power exchanged: Qatar-400kV-750MW, Behrain-400kV-600MW, UAE-400kV-900MW and Oman-220kV-400MW, Kingdom Saudi Arbia-400kV-1200MW, Kuwait-400kV-1200MW. Appendix.6.A indicates SSSC device optimum location for installation at GCC power grid. Tables 6.9 shows the SSSC'S capacitive and inductive modes of operation as defined to improve voltage profile, power angle and stability margins in between (Oman and United Arab Emirates,) and its impact on neighboring countries power system facilities [1],[2]. (1) Increased power transfer capability in the GCC power grid. (2) Improved GCC power grid operational reliability. (3) Improved GCC power grid controllability. Figure 6-1 illustrates the designed power exchange in between GCC countries and Figure 6-2 an inter-tie connection with SSSC in between the GCC countries. Figure 6-3 shows the Matlab simulated model's components. Prime contributions of this research work are as listed below.

1. Investigate the STATCOM impact on GCC power grid by implementing new optimization control technique and compare the GCC Power grid system operations with and without STATCOM.

After successful implementation of STATCOM device will enahnce the network loadability and voltage profile. The rest of this research study is structured as follows. After the introduction section, the GCC power system background, the system reinforcement plan, the FACTS device selection process, and the STATCOM Model description are described in sections 6.2, 6.3, 6.4, and 6.5. The STATCOM model's optimized dynamic performance, observations and conclusion/results are described in sections 6.6, 6.7 and 6.8 [4], [5].

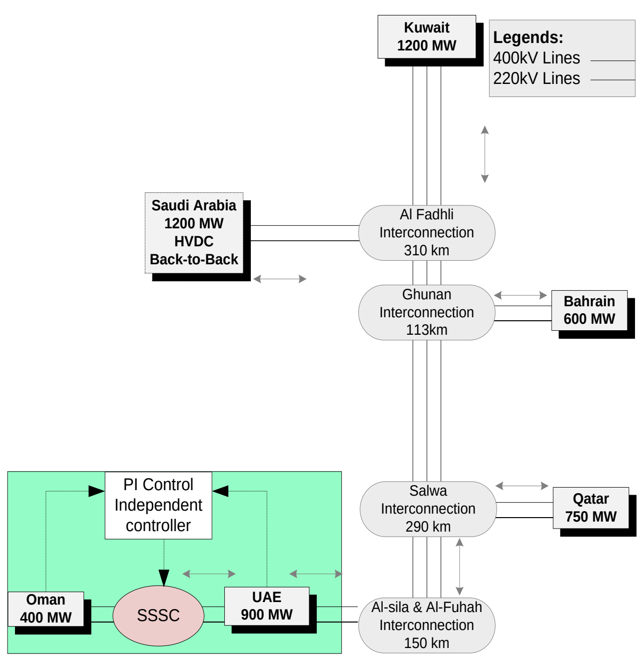


Figure 6-1: Simplified SSSC control schematic share/deliver 400MW power at the Oman side and 900MW at the United Arab Emirates

6.1.1. GCC Power System Background Information:

The GCC power system facilities are configured and implemented into 8 strategic ways to meet reliable and sustainable industrial and domestic power system requirements at the Gulf Corporative Council power network as shown in Figure 6-2. Firstly, a double-circuit 400 kV, 50 Hz line stretching from Al Zour (Kuwait) to Ghunan (Saudi Arabia) with an intermediate connection at Fadhili (Kingdom Saudi Arabia) and its associated power system facilities was installed. Secondly, a back-to-back HVDC link introduced as a 380 kV interconnection, 60 Hz, system at Fadhili (KSA) in order to maintain proper synchronization or communication with other GCC power systems, which are operating at 50Hz frequency was also installed. Thirdly, a double circuit 400 kV overhead line stretching and partially connected with submarine link from Ghunan (KSA) to Al Jasra (Bahrain) along with its associated power system facilities was installed. Fourthly, a double circuit 400 kV line stretching from Ghunan (KSA) to Salwa (QATAR) into Saudi Arabia along with its associated substations was installed. Fifthly, a double circuit 400 kV line stretching from Salwa (Qatar) to Doha South and its associated facilities was installed. Sixthly, a double circuit 400 kV, 50 Hz line stretching from Salwa (Qatar) to Ghuwaifat (United Arab Emirates) along with its associated power system facilities was installed. Seventhly, a double and a single circuit 220 kV,50Hz line stretching from Al Ouhah (United Arab Emirates) to Al Wasset (Oman) along with its associated substations was installed. Finally, a centralized control room was established at Ghunan (KSA) in order to control power system operations within all GCC countries with a certain degree of precision at different voltage and shared power perspective [4], [5].

6.1.2. Power System reinforcement plan in between the Oman and UAE:

In order to initiate a proper power system reinforcement plan, multiple studies at different voltage levels have been completed to determine the power system operational requirements at both sides of the United Emirates and Oman. This study reveals the Oman and United Arab Emirates substation sites are selected for the SSSC installation for the following reasons: firstly as demonstrated in the GCC power system background, Oman and the United Arab Emirates have an interconnection with industrial and domestic consumers at Al-Fuhah (United Arab Emirates) and Al-Wasset (Oman) power facilities. Based on the power authorities investigation report which identified that a couple of stability issues may exist on their systems, and consequently, also on the consumers' side of the system. This is very much viable to utilize the ability of the SSSC to improve all types of existing and potential stability issues in between Oman and the United Arab Emirates' power system facilities. The second strategic approach, as demonstrated in Figure 6-2, shows the main transmission line coming out from KSA, Kuwait, Qatar, Bahrain, the United Arab Emirates 400kV bus is exposed to an increase in voltage levels during light load conditions due to the inherent shunt capacitance of the 400kV transmission line. Likewise, the 220kV bus is exposed to a reduction in voltage levels during peak load conditions on both sides of United Arab Emirates and Oman. The Al-Fuhah substation (UAE) and Al-Wasset Substation (Oman) sites are the best locations on the Oman and United Arab Emirates network where the total symmetrical range of the reactive output from the SSSC, from full inductive to full capacitive, could be utilized without applying fixed capacitors

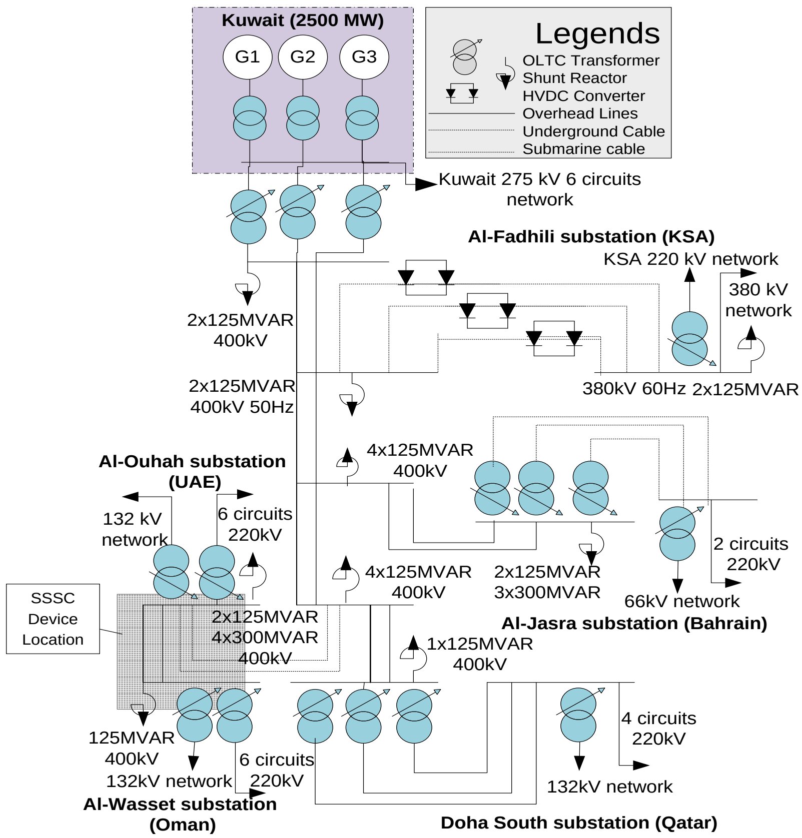


Figure 6-2: Proposed area (shaded) for SSSC implementation in between the United Arab Emirates and Oman

6.1.3. SSSC Mathematical Model

Figure 6-3 shows an SSSC simulated model at the midpoint of the transmission line on the GCC power grid. The transmission line is modeled with lumped impedances. The voltages $V_1\angle\theta_1$and $V_2\angle\theta_2$are midpoint voltages on each side of the SSSC, and the $V_{inj}\angle\theta_{inj}$ represents the voltage injected by the controller [9]. The SSSC model is similar to that of STATCOM.

$$\frac{1}{\omega_s}\frac{d}{dt}i_d = -\frac{R_s}{L_s}i_d + \frac{\omega}{\omega_s}i_q + \frac{k}{L_s}\cos(\alpha+\theta_i)\,V_{dc} - \frac{1}{L_s}(V_2 cos\theta_2 - V_1 cos\theta_1) \tag{6.1}$$

$$\frac{1}{\omega_s}\frac{d}{dt}i_d = -\frac{R_s}{L_s}i_d + \frac{\omega}{\omega_s}i_q + \frac{k}{L_s}\sin(\alpha+\theta_i)\,V_{dc} - \frac{1}{L_s}(V_2 sin\theta_2 - V_1 cos\theta_1) \tag{6.2}$$

$$\frac{C}{\omega_s}\frac{d}{dt}V_{dc} = -k\cos(\alpha+\theta_i)\,i_d - ksin(\alpha-\theta_1)i_q - \frac{V_{dc}}{R_{dc}} \tag{6.3}$$

Where $V_1\angle\theta_1$ and $V_2\angle\theta_2$ are the terminal voltages of the SSSC. Therefore, the power balanced equations at the sending end of the SSSC at bus 1 are given as:

$$0 = -V_1(i_d cos\theta_1 + i_q sin\theta_1) - V_1 \sum_{j=1}^{n} V_j Y_{1j} \cos(\theta_1 + \theta_j - \emptyset_{1j}) \quad (6.4)$$

$$0 = -V_1(i_d sin\theta_1 + i_q cos\theta_1) - V_1 \sum_{j=1}^{n} V_j Y_{1j} \sin(\theta_1 + \theta_j - \emptyset_{1j}) \quad (6.5)$$

And at the receiving end at bus 2 (power balance equations)

$$0 = -V_2(i_d cos\theta_2 + i_q sin\theta_2) - V_2 \sum_{j=1}^{n} V_j Y_{2j} \cos(\theta_2 + \theta_j - \emptyset_{2j}) \quad (6.6)$$

$$0 = -V_2(i_d sin\theta_2 + i_q cos\theta_2) - V_2 \sum_{j=1}^{n} V_j Y_{2j} \sin(\theta_2 + \theta_j - \emptyset_{2j}) \quad (6.7)$$

The PWM switching is used to govern the switching, then

$$V_{inj} = kVdc = k_{tr} maVdc \quad (7.8)$$

$$\theta_{inj} = \theta_1 + \alpha \quad (7.9)$$

Herein, k and α are the PWM modulation gain and phase shift. The modulation gain k is proportional to the modulation index ma and k_{tr} which are determined by the modulation method and the serial transformer winding ratio. The range of ma & α are constrained by the steady-state reactive power capabilities of the controller. The Phasor diagram of the SSSC; where it has been assumed that $VS = VR \text{ and } \delta S = \theta S + \theta R$ The phase shift α is referenced to $\theta 1$ since it is not practical to synchronize the injected voltage to the system reference. This diagram can be used as a basis from which to derive a control approach. If losses are neglected, then the injected powers P_{inj} and Q_{inj}, and the output powers P_{out} and Q_{out} can be denoted as follows:

$$P_{inj} = \frac{V_{inj}V}{X}(sin\theta_{inj} - \sin(\theta_{inj} - \delta)) = \frac{V(E_q - E_q cos\delta + E_d sin\delta)}{X} \quad (6.10)$$

$$Q_{inj} = \frac{V_{inj}}{X}(Vcos(\theta_{inj} - \delta) + V_{inj} - V\cos\theta_{inj}) = \frac{(VE_q cos\delta - VE_q sin\delta + VE_d + V^2{}_{inj})}{X} \quad (6.11)$$

$$P_{out} = \frac{V^2 sin\delta + VV_{inj} sin\theta_{inj}}{X} = \frac{(V^2 \sin\delta + VE_q)}{X} \quad (6.12)$$

$$Q_{out} = \frac{2V_{inj}Vcos(\delta - \theta_{inj}) + V^2{}_{inj}}{X} = \frac{(2VE_q \quad \sin\delta + V^2{}_{inj})}{2X} \quad (6.13)$$

$$E_q = V_{inj} sin\theta_{inj} \quad (6.14)$$

$$E_d = V_{inj} cos\,\theta_{inj} \quad (6.15)$$

$V_{inj}^2 = E_d^2 + E_q^2$ (6.16)

$\theta_{inj} = \pm\frac{\pi}{2} + \frac{\delta}{2}$ (6.17)

$P_{inj} = 0$ (6.18)

Note that the compensated SSSC voltage vector V_2 will remain in the line *ab* since the injected voltage V_{inj} must be perpendicular to the current *i* at all times. The above Phasor diagram and the relationship described above provide a frame work in which to develop a systematic control scheme for the SSSC. The power-flow control capability of an SSC is constrained by its pure reactive power compensation capability during steady-state operation. The traditional approach to PWM-based SSSC control is to use the modulation index ma to adjust the compensated apparent impedance, while using the phase shift to charge or discharge the DC capacitor. Since the control effect of *ma* and *α* interact with each other, it is described to introduce to new constrained decoupled control variables $\Delta Ed \text{ and } \Delta Eq$ to obtain the control target. Under normal operation, the phase angle between adjacent buses is relatively small[9].

Therefore, since δ is small, then $(1 - cos\delta) \approx 0$ and

$\Delta P_{inj} = \frac{V}{X}\Delta E_d sin\delta$ (6.19)

Limited by the lack of an active power source on the dc side from which to absorb or inject energy, it is therefore important to control the injected active power close to zero to maintain near constant dc voltage across the VSC capacitors. A nearly constant DC voltage is important since it directly affects the control speed and effectiveness of the SSSC. ΔEd is the main factor in affecting the injected active power, thus ΔEd can be used to adjust the dc capacitor voltage around its reference value. By combining the controls for dc voltage and transmission line active power flow, a constrained decoupled PI control algorithm for SSSC is given by:

$\Delta E_q = k'_{pp}\Delta P_2 + k'_{pi}\int \Delta P_2 dt$ (6.20)

$\Delta E_d = k'_{vp}\Delta Vdc \quad + k'_{vi}\int \Delta V_{dc} dt$ (6.21)

In implementation, these quantities are combined with the initial operating point and converted into a modulation index *ma* and phase shift *α s*uch that

$ma = \frac{\sqrt{E_d^2+E_q^2}}{k_{tr}V_{dc}}$ (6.22)

$$\alpha = sin^{-1}\left(\frac{E_q}{\sqrt{E_d^2 + E_q^2}}\right) - \theta_1, \ldots E_d > 0$$

$$= \pi - sin^{-1}\left(\frac{E_q}{\sqrt{E_d^2 + E_q^2}}\right) - \theta_1, \ldots E_d <; eq > 0$$

$$= -\pi - sin^{-1}\left(\frac{E_q}{\sqrt{E_d^2 + E_q^2}}\right) - \theta_1, \ldots E_d <; eq > 0 \qquad (6.23)$$

Where $E_q = E_{q0} + \Delta E_q$, $E_d = E_{do} + \Delta E_d$, (6.24)

$E_{q0} = k_{tr}\, m_{a0}\, V_{dc} \sin(\alpha + \theta_1)$ (6.25)

$E_{d0} = k_{tr}\, m_{a0}\, V_{dc} \cos(\alpha + \theta_1)$ (6.26)

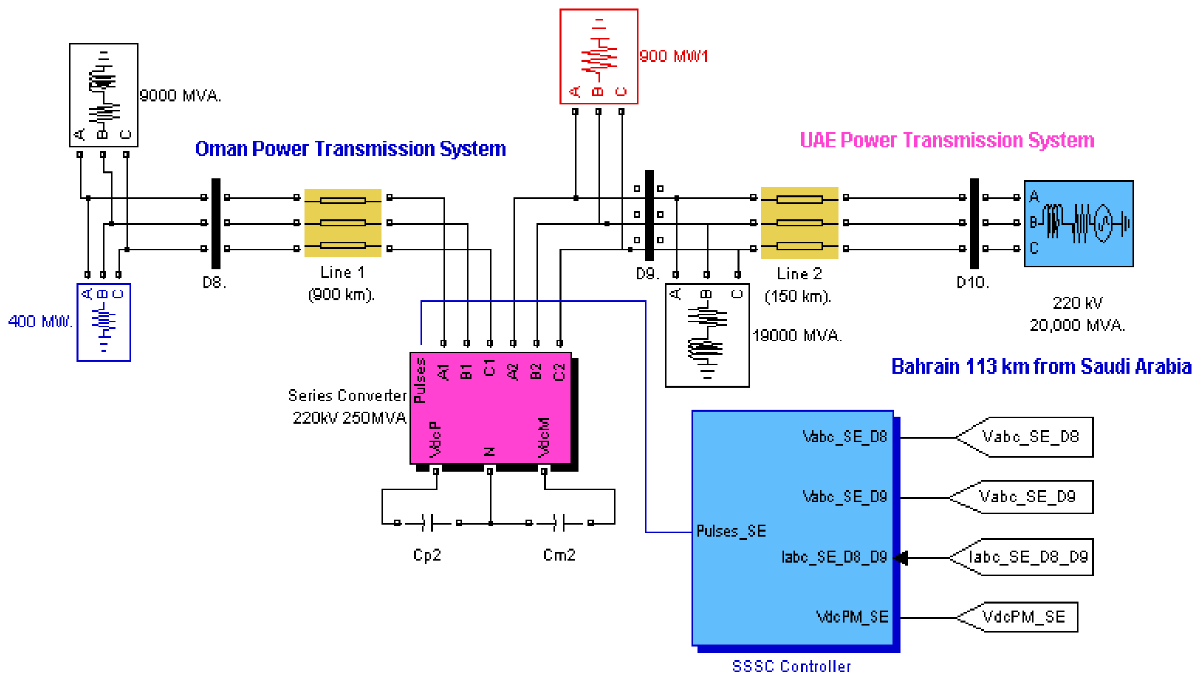


Figure 6-3: simulated SSSC control schematic in between Oman and United Arab Emirates

6.1.4. SSSC model's distributed control:

Appendix 6.A introduced and demonstrated that the SSSC control model's three distributed control limits are defined as minimum, medium and maximum. These deviations are compensated at three operating limits by adjusting the SSSC control device with corresponding P & I control values as stated in Appendix 6.A Table. The SSSC control device oscillates based on the corresponding P & I value of each limit in between at +/-2%, +/-4% and +/-6% deviation at both sides of the transmission lines to adjust reactive power compensation as required. These control boundaries customized P &I values are enabling the control system to communicate each limit accurately and adjust the reactive power compensation based on sending and receiving ends voltage based deviations at different locations on the GCC power grid. These control boundaries will effectively operate when more than one FACTS device will be in operation at different locations on the GCC power grid. These will communicate to each other based on voltage, impedance, angle and power deviation at the sending and receiving ends of the Oman and United Arab Emirates power system facilities.

6.2. SSSC controller's selection process

The Wideband Delphi technique was used by incorporating various technical committees input to determine and develop prolific consensus to allot estimated values of significance and submission criteria(s) as demonstrated in Table 6.1. These 12 areas input values are compiled and estimated based on SSSC control device operational significance. Table 6.2 indicates the estimated values of each FACTS device based on their operational and control capability between Oman and the United Arab Emirates that are obtained by using the Wideband Delphi Technique. Table 6.3 demonstrates the FACTS devices submission criteria to decide and select the most appropriate control device. The equation (6.27) represents the calculation method to identify the CRV_Z value of an individual FACTS device based on the estimated statistical data as provided. Herein, the CRV_Z model described its different parameters by the following equation [14].

$$.CRV_Z = \sum_{n=1}^{12} \frac{B_n}{100} xCn = \left(\frac{B_1}{100} xC1 + \frac{B_2}{100} xC2 + \frac{B_3}{100} xC3 \ldots . + \frac{B_{12}}{100} xC12\right) \qquad (6.27)$$

Where:

Z(subscript) STATCOM, SSSC, UPFC, IPFC,SVC……………n

CRV_{SSSC} (credible value)

B_1 to B_{12} (Significant criteria as per Table 6.1)

C (Constant value of each device as shown in Table 6.2)

Based on this calculation method each device CRV_Z value is derived and illustrated into Table 6.4 and 6.5. After successful evaluation, however, it has been determined that the SSSC device obtained a high weighted score compared to other devices. Based on the results, this is a strong candidate to implement between Bahrain and Qatar. Thus the Wideband Delphi technique can be used effectively to develop a prolific consensus to allot estimated values of significance and submission criteria(s) as demonstrated in Table 5.1 & 5.2. If the summation score of table 6.4 and 6.5 of any device is above 65 it means a good submission and 80 significant (strong candidate). Therefore, the Wideband Delphi technique has been given very prolific supporting results in order to formulate the selection process of FACTS devices more pragmatically. This equation comprises of 12^{th} section corresponding to Table

6.1 as an input data from B1 to B12 this is also called the nominator and first part of the equation (6.27). These 12 areas total output value must be equal to 100. This is also called the denominator and second part of the equation (6.27). Third part of the equation is "C1 to C12" this is submission value of each segment of 12 areas as demonstrated into Table 6.2. During the calculation process the numerator is divided by the denominator and multiple with "C1 to C12" values in order to get final value of the each segment as indicated in Table 6.4. *(See section 5.2 for further details about the WBD)*

TABLE 6.1: SSSC DEVICES CRITERIA SIGNIFICANCE

S.No	Criteria	Weight (%)	S.No	Criteria	Weight (%)
1	Control Significance	15	7	Refuse Disposal	5
2	Control Integration	10	8	Monitoring Equipment	5
3	Design Capacity	5	9	Simulation Results	5
4	Reliability	10	10	Capex	10
5	Maintenance frequency	15	11	Opex	10
6	Availability for field trial	5	12	Post Installation Support	5
			Total		100

TABLE 6.2: SSSC DEVICE ESTIMATED SCORE

Device	Submission Score	Device	Submission Score
TCVR	46	STATCOM	68
TCPAR	49	SVC	57
UPFC	63	GCSC	41
IPFC	59	TSSC	36
SSSC	74.3	TCSC	43

TABLE 6.3: FACTS DEVICES SUBMISSION CERITERIA SCOREBOARD

Criteria Description	:	Submission Score
No submission of any consequence	:	0
Some submission but unacceptably low	:	20
Satisfactory	:	50
Good submission	:	65
Significantly above the minimum acceptable. Considered a strong candidate.	:	80
Exceptional submission	:	100

TABLE 6.4: CALCULATED SCORE BY USING EQUATION 6.27

Criteria	$B_{1\ldots12}$	$C_{1\ldots12}$	Equation (5.8)	Weighted Score
Control Significance	15	67	$(B_1/100).C_1$	10
Control Integration	10	90	$(B_2/100).C_2$	9
Design Capacity	5	96	$(B_3/100).C_3$	4.8
Reliability	10	95	$(B_4/100).C_4$	9.5
Maintenance frequency	15	60	$(B_5/100).C_5$	9

Availability for trial	5	98	$(B_6/100).C_6$	4.9
Refuse disposal	5	96	$(B_7/100).C_7$	4.8
Monitoring equipment	5	96	$(B_8/100).C_8$	4.8
Simulation results	5	94	$(B_9/100).C_9$	4.7
Capex	10	85	$(B_{10}/100).C_{10}$	8.5
Opex	10	95	$(B_{11}/100).C_{11}$	9.5
Post Installation Support	5	96	$(B_{12}/100).C_{12}$	4.8
Total	100	-	-	74.3

TABLE 6.5: SSSC DEVICES CALCULATED SCORE AGAINST THE OTHER DEVICES

Static Shunt Compensator			**Static Series Compensator**		
STATCOM		SVC	GCSC	TSSC	SSSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	7.8	6.7	4.8	4.1	10
2	8.2	7	5	4.3	9
3	6.1	5.2	3.7	3.2	4.8
4	7.5	6.4	4.6	4	9.5
5	6.8	5.8	4.2	3.6	9
6	4.4	3.8	2.7	3	4.9
7	5.4	4.6	3.3	3	4.8
8	5.1	4.4	3.1	3	4.8
9	4.4	3.8	3.5	2.5	4.7
10	4.4	3.8	3.5	3	8.5
11	4.5	3.5	3	3	9.5
12	4.4	4	3.5	3.3	4.8
Total	69.0	59.0	45	40	74.3

TABLE 6.6: SSSC DEVICES CALCULATED SCORE AGAINST THE OTHER DEVICES

Static voltage and phase Angle control			**Combined Compensator**		**Static Series Compensator**
TCVR		TCPAR	UPFC	IPFC	TCSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	5.3	5.7	7.2	6.8	4.9
2	5.6	5.9	7.6	7.1	5.2
3	4.2	4.5	5.7	6	3.9
4	5.1	5.4	6.9	6.5	4.7
5	4.7	5	6.3	5.9	4.3
6	3	3.2	4.5	4.5	2.8
7	4	4	5	4.7	3.4
8	4	3.7	4.7	4.4	3.3
9	3	4	4.5	4	3.5
10	3	4	4.3	4	3
11	3	3.5	3.8	4	2.6
12	3	3.1	3.5	4	2.4
Total	48	52	65	62	44

TABLE 6.7: DEFINED POWER AND SYSTEM'S VOLTAGE

Country Id	**Country Name**	**Power ID**	**Mw**	**Voltage ID**	**Line Voltage kV**
C1	Kuwait	PC1	1200	V1	400
C2	Saudi Arabia	PC2	1200	V2	400
C3	Bahrain	PC3	600	V3	400
C4	Qatar	PC4	750	V4	400
C5	Oman	PC5	400	V5	220
C6	United Arab Emirates	PC6	900	V6	400
C6	United Arab Emirates	PC7	400	V7	220

6.3. SSSC model's case study (Oman & United Arab Emirates):

Table 6.8, 6.9 and 6.10 indicates the SSSC input data that is used to develop and simulate the SSSC control model. A 250-Mvar SSSC control model was developed to adjust converter output voltage in order to maintain the 220kV AC system long transmission line in Oman and the United Arab Emirates. In the steady operation of SSSC control device maintain the Voltage source converter's fundamental components in-phase with the AC system in between Oman and UAE. In the first scenario if the converter output voltage is higher than the system voltage than the SSSC generates the reactive power to increase the system voltage against the reference value. If the AC system voltage is higher than the converter output voltage than the SSSC absorbs reactive power from the system to reduce the voltage. It has been identified and determined that the amount of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance. The voltage source converter components are controlled by varying the DC bus voltage. In order to charge or discharge the capacitor bank of the SSSC the VSC (Voltage source converter) is temporarily phase shifted to flow active power to the capacitor bank. Figure 6-4 Illustrates the 400 MW power exchanged between Oman and the United Arab Emirates into the shared GCC Power grid. As shown by the waveforms, the transmission line voltage and reactive current are well controlled by implementing the optimized control technique with a high degree of precision [45], [59]

TABLE 6.8: POWER, VOLTAGE AND FREQUENCEY

Countries	Power Exchange, Voltage & Frequency
To/from Oman power transmission network	400MW, 220kV, 50Hz
To/from United Arab Emirates transmission network	900MW, 220kV, 50Hz

TABLE 6.9: EXISTING REACTIVE POWER AND DISTANCE

Existing Power System	Reactive Power	Distance
Reactive Power Demand at Al-Ghunan substation KSA	500MVAR	Al Fadhili substation (KSA) to Al-Ghunan Substation (KSA) =114 Km
Reactive Power Demand at Al Jasra substation Bahrain	850MVAR	Al-Ghunan Substation (KSA) to Slawa Substation (Qatar) = 288Km
Reactive Power demand at Al-Salwa Substation	500MVAR	Slawa Substation (Qatar) to Doha South Substation = 97Km
Reactive Power demand at Doha South Substation	250MVAR	

TABLE 6.10: MULTIVARIABLE CONTROLLER'S CONFIGURATION OF THE SSSC

SSSC LOCATION: Series connected at Al-wasset substation in between Oman and United Arab Emirates	Iq regular: Kp 12dB; Ki: 35dB	CC2 and LC2 = minimum compensation capacitive or inductive (VC voltage change from 1 to 2%)
Rated SSSC: +/- 250 MVAR	Ref V: 1.0 pu (220kV)	CC22 and LC22 = medium compensation capacitive or inductive (VC voltage change from 2% to 4%)
P (proportional): 0.32 , 0.42 and 0.52 **I (integral) 0.6, 0.8, 0.9, 1.1** **D (derivative): none**	Droop: 0.033pu/100MVA; Kp:14dB; Ki: 3500dB	CC222 and LC222 = full compensation capacitive or inductive (VC voltage change from 4-6%)

6.3.1. ***SSSC optimized dynamic response:***

Figure 6-4 shows the operations of the SSSC, and it controls the AC system voltage against the set reference voltage 1.0 pu. Effectively to control the deviation the regulator is maintaining voltage droop 0.035 pu/100 VA. Based on the voltage deviation the SSSC device changes its operating point from full capacitive or inductive (+/-250Mvar) as demonstrated into Figure 6-5. The first waveform of the SSSC controller in voltage control mode and demonstrate voltage variation between 0.95 to 1.05 pu. The VSC (voltage source converter) is set at 1.045pu, which maintain SVC terminal voltage 1.0pu and the SSSC controller is out of operation. Initially the SSSC is floating at zero current and the reference voltage set at 1.0pu and the DC bust voltage is 20kV. After 0.15s the voltage drastically decreased by 2.7% (0.982pu) of the normal voltage of the AC system. Based on the deviation the SSSC actives and inject 250Mvar to the AC system in order to maintain 0.985pu of the normal voltage. After 45ms the DC bus voltage increased accordingly and the AC system voltage also reached at 1.05pu within 0.3s of its normal voltage. Based on this the deviation the SSSC activates and absorb reactive power 250Mvar from the AC system in order to maintain theca system voltage 0.95pu [47].

It has also been observed that the SSSC current changed from capacitive to inductive within one cycle. After 0.65s the voltage source converter (VSC) set back to normal value based on the deviation. The second waveform indicates the phase Iabc current during the above-mentioned SSSC operations.

i) The third waveform indicates the magnitude of voltage injected against the reference voltage.
ii) The third waveform indicates the measured DC voltage (15kV/Maximum) during the inductive or capacitive mode of SSSC operations.
iii) The fourth waveform indicates the Real power being exchanged in between United Arab Emirates and Oman during SSSC operations.
iv) The fourth waveform indicates the required reactive power being injected in between United Arab Emirates and Oman during SSSC operations.

In Figure 6-5, it can be seen that both sides of network voltages are improved which are controlled precisely to optimize SSSC operations in order to exchange the required power from both sides of the United Arab Emirates and Oman on the GCC power grid.

6.3.2. Effectiveness of the SSSC control device:

Figure 6-4 indicates the receiving ends voltage without SSSC in between the United Arab Emirates and Oman. Figure 6-5 shows the improved voltage with SSSC at both receiving ends at the United Arab Emirates and Oman.. These results obtained after implementation of PID new configuration control parameters. Figure 6-5 further demonstrates the SSSC effectiveness on the GCC power grid.

In the first trace, the waveforms show Vref (magenta trace) and measured voltage (yellow trace) variation from 1pu to 0.98pu and 1pu to 1.03pu. In the second trace, the variations in Iqref (magenta trace) and Iq(yellow trace) waveforms are observed. It is noticed that the measured Iq _ oscillated from -1.8pu to 1.7pu on the same path of Iq_ reference and, it then leveled to a steady state value after 0.35 s.

In the third trace, a variation in real and reactive powers P and Q are observed; the Q value oscillates to compensate the required reactive power as per defined boundary from -1pu to 1pu(+/- 250 Mvar). In the last trace, the behavior of alpha angle is observed; in this case, there is small oscillation from 0.05 to 0.1 s. In order to enforce a corrective action to minimize the error, all observations are addressed by adjusting the control parameters precisely by considering adequate safety and security margins [36], [37].

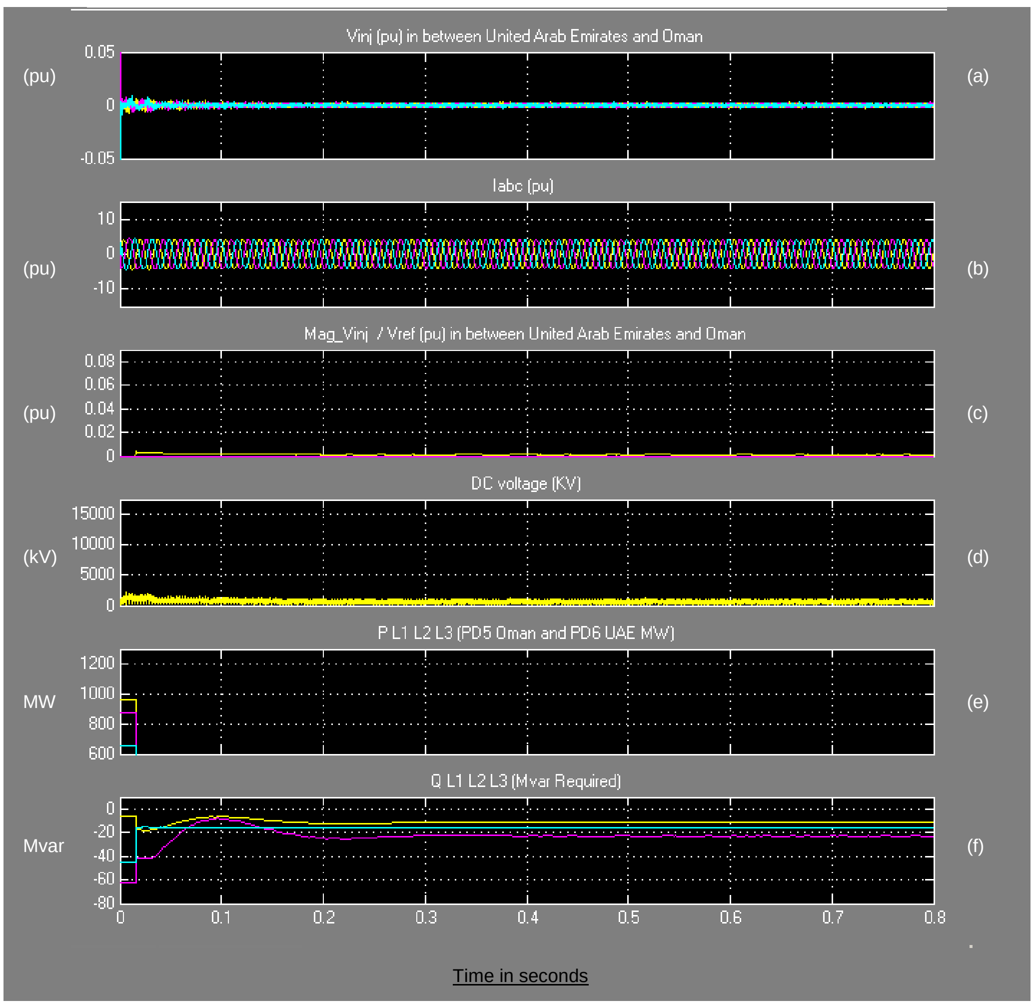


Figure 6-4: Network operational trends without SSSC (a) voltage injection (b) Iabc current (c) injection voltage magnitude and reference voltage (d) DC voltage (e) power exchange in between Oman and UAE (f) reactive compensation in between Oman and UAE

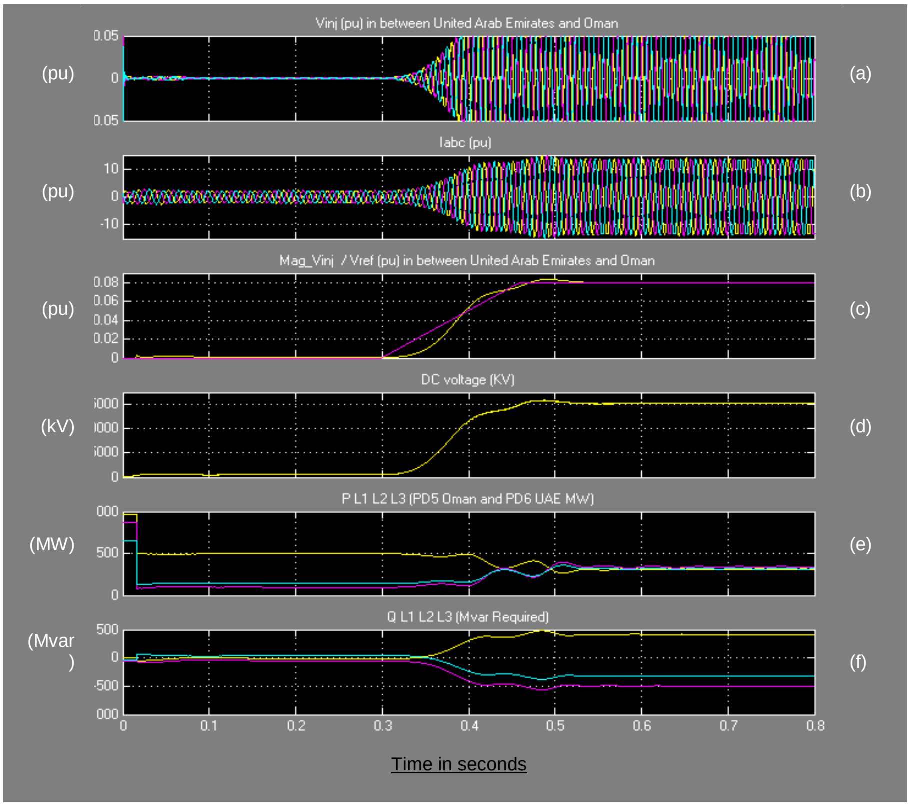


Figure 6-5: indicates the network operational trends with SSSC (a) voltage injection (b) Iabc current (c) injection voltage magnitude and reference voltage (d) DC voltage (e) power exchange in between Oman and UAE (f) reactive compensation in between Oman and UAE

6.4. Observations:

Figure 6-5 illustrates the analysis of SSSC key parameters at the United Arab Emirates Al-Fuhah Substation and Al-Wasset Substation (Oman). In the first trace, the waveforms show injected voltage +/-0.05pu which improves the SSSC operations significantly. The second trace indicates phase current operations which oscillate +/- 10pu at s=0.35 second. The third trace shows the magnitude of voltage injected against the reference voltage after 0.34 second. The fourth trace shows the DC voltage increased from zero to 15kV after 0.3 second and remained at the same value for the rest of the SSSC operations. The fifth and sixth traces indicate change in reactive and real power within a given time span. In order to enforce a corrective action to minimize the error, all observations are addressed by adjusting the control parameters precisely by considering adequate safety and security margins.

6.5. Results and discussion:

The SSSC control model has developed into three control limits that are defined to adjust reactive power compensation; minimum, medium and maximum. These control limits are defined against their corresponding PI control values in Appendix 6.A. Simulation results indicate that the SSSC controller oscillates between +/-2, 4 and 6% at both sides of transmission lines to adjust reactive power compensation as required. These control boundaries will communicate and adjust reactive power based on sending and receiving ends voltage deviation. The controller will oscillate and inject or absorb controlled reactive power based on corresponding PI controller values of each operating boundary as demonstrated in Appendix 6.A. These control boundaries will effectively operate when more than one FACTS device will be in operation at different locations on the GCC power grid in order to share 900 MW power from UAE and 400 MW power from Oman. These will communicate to each other based on voltage, impedance, angle and power deviation at the sending and receiving ends of the AC power system.

The prime aim of the SSSC application in the GCC power grid transmission line compensation is the subject of considerable interest. The results show that SSSC is a versatile equipment with outstanding dynamic capability, as aforementioned, and is able to provide reliable continuous control to the power transmission line current, provide dynamic control of power flow, reduce fault current, damps SSR oscillation, improves the voltage profile, the power angle and the stability margin between Oman and the United Arab Emirates. Based on these results, SSSC is a very strong candidate to be implemented on the GCC power grid. It also exhibits a positive impact on neighboring countries' power system operations on the GCC power grid.

6.6. Summary:

In this chapter, the SSSC device model demonstrates its strong impact on stability and medium impact on power flow between Oman and the United Arab Emirates. The Oman power network shares the 400MW power and United Arab Emirates power network shares the 900MW.

Collectively, this device will enhance power system stability and power flow in order to share 900MW power from the United Arab Emirates and 400MW power from Oman to meet industrial and domestic loads requirements at different atmospheric (summer/winter) operating conditions on the GCC power grid. Hereby, the GCC power system background and viabilities are also addressed as well as the SSSC reinforcement plan. In addition to that, the SSSC control model's new control optimization and device selection techniques are described in detail and its application in order to resolve various control and operational issues precisely. Based on these control techniques three control limits along with corresponding PID new control values are incorporated into the SSSC model and simulated as demonstrated in appendix 6.A. These control techniques are providing a lot of confidence to operate SSSC device independently or jointly (integrated) as further discussed in chapter 9.

CHAPTER 7

The UPFC connecting the Kingdom of Saudi Arabia and Kuwait in the GCC interconnection

7.1. Introduction:-

The proposed work is a non-traditional novel optimization technique that has been adopted to optimize the various UPFC control and operating parameters that contribute notably to control UPFC device operations in a power system network during any undesired condition. The UPFC controller is a strong candidate to provide a full dynamic control of Power transmission operating parameters: voltages, line impedance, and phase angle. Herein, the UPFC applications are investigated to analyze viability in order to improve the power transmission control and enhance operational performance from one grid to another grid at the GCC power system. This research presents a novel control and operation of a UPFC connecting the Kingdom of Saudi Arabia (KSA) and Kuwait in the Gulf Cooperative Council Interconnection. The proposed control optimizes UPFC control parameters, improving the UPFC performance at different transmission contingencies. The credibility of the proposed control is evaluated through a set of time simulations. The results have clearly shown an increase of the loadability, reduction of the losses and enhancement of the sustainability on the GCC Interconnection. The GCC region has become a hub of major economic growth in the world. It is providing financial support and incentives to the GCC countries. Hereby, it has witnessed population growth and large scale industrial activities in the GCC countries. This has led to increased demand for electricity. Based on various analyses, we determined that the current demand for GCC power consumption is about 60 GW and it is projected that it will reach 180 GW within next 25 years. In order to maintain a reliable, sustainable, and well-controlled power transfer between the GCC countries, it has been decided to interconnect the GCC countries. The interconnection is divided into two basic segmental links, neighbor-to-neighbor and common-link topologies. Firstly, Oman and the United Arab Emirates are interconnected through neighbor-to-neighbor control topologies. Secondly, Qatar, Bahrain, Saudi Arabia and Kuwait are interconnected through common-link control topology and this is also known as the Northern System. In the third stage common-link topology demonstrates UAE national grid and Oman northern grid interconnection; this is known as southern systems. Thirdly, southern and northern power systems are connected through hybrid link control topology. However, to improve these interconnected topologies, a large numbers of studies have been conducted to determine the technical and economical viability of the interconnection. The studies also demonstrate areas that require additional control devices. FACTS controllers are, therefore, strong candidates' technology options. Applications of FACTS Controllers will result into the following benefits [1], [2]. (1) Enhanced Power Transfer capability in the GCC power grid. (2) Enhanced the GCC power grid's operational reliability. (3) Enhanced the GCC power grid's controllability. Figure 7-1 illustrates the designed power exchange in between the GCC countries and Figure 7-2 indicates the location of UPFC and an inter-tie connection in between the GCC countries and Figure 7-3 shows the simulated model of the UPFC device. Prime contributions of this research work are as listed below.

i) Investigate the UPFC impact on GCC power grid with new PID controller optimization technique.

ii) Investigate the GCC power grid operations with and without UPFC control device

The rest of this research case study is structured as follows. In section, 7.2 and 7.3 GCC power system background and UPFC reinforcement plan are described. In section 7.4, 7.5, 7.6 UPFC Model description, operational strategy and operating performance are described. In section 7.7, 7.8 discussion, and conclusion are presented.

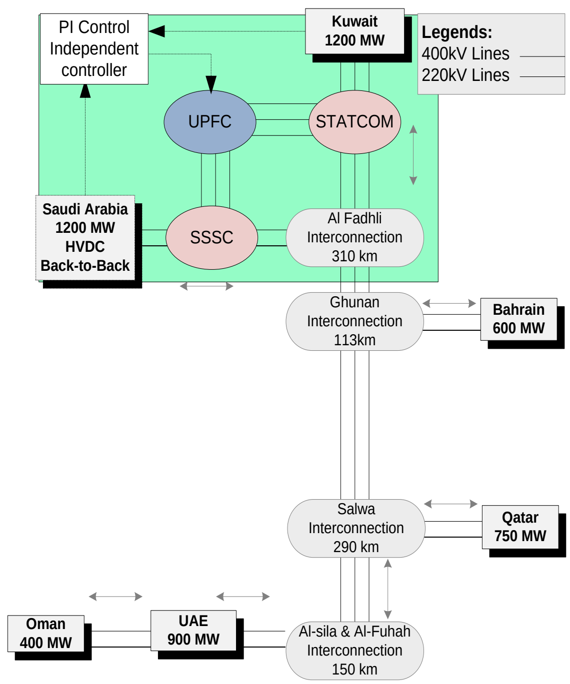


Figure 7-1: location of UPFC device in between the Kingdom Saudi Arabia and Kuwait

7.1.1. GCC interconnection background:

The GCC power grid is designed to operate in eight strategic directions to meet sustainability and operational reliability requirements as demonstrated in Figure 7-2. The first section is a double-circuit 400 kV, 50 Hz line stretched from Al Zour (Kuwait) to Ghunan (KSA) with an intermediate connection at Fadhili (KSA) power facilities. The second section is a back-to-back HVDC tie interconnecting the 380 kV, 60 Hz, system at Fadhili in the KSA. The third section is a double circuit 400 kV overhead line stretched and partially connected with a submarine cable from Ghunan (KSA) substation to Al Jasra (Bahrain). The fourth section is a double circuit 400 kV line stretched from Ghunan (KSA) to Salwa (Qatar) along with its associated substations. The fifth section is a double circuit 400 kV line stretched from Salwa (Qatar) and its associated substations. The sixth section is a double circuit 400 kV, 50 Hz line stretched from Salwa (Qatar) to Ghuwaifat (UAE) along with its associated substations. The seventh section is a double and a single circuit 220 kV, 50Hz transmission line stretched from Al Ouhah (UAE) to Al Wasset (Oman) along with its associated substations. The eighth section is a centralized control room that has been established at Ghunan (KSA) in order to control power system operations within all the GCC countries with a high degree of precision at different voltage. [5], [6].

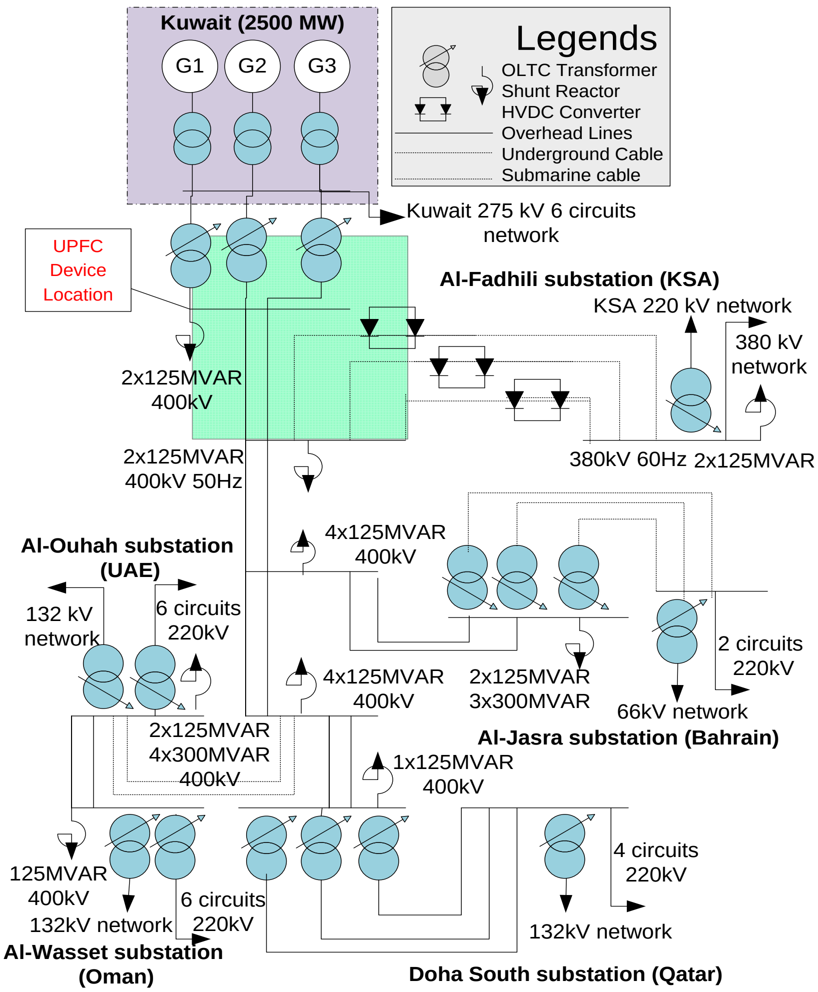


Figure 7-2: interconnection of UPFC device in between the Kingdom Saudi Arabia and Kuwait

7.1.2. UPFC Mathematical Model

Figure 7-3 shows the simulated UPFC device which is the most versatile FACTS device. It consists of combination of shunt and series branches (STATCOM and SSSC) connected through the dc capacitor[9]. The series connected inverter injects a voltage with controllable magnitude and phase angle in series with the transmission line, therefore providing real and reactive to the transmission line. The shunt connected inverter real power drawn by the series branch and losses and can independently provide reactive compensation to the system. The UPFC model is a combination of STATCOM and SSSC Models.

$$\frac{1}{\omega_s}\frac{d}{dt}i_d = -\frac{K_1 dc}{L_s}\cos(\alpha_1+\theta_1)+\frac{\omega}{\omega_s}i_{q1}-\frac{R_{s1}}{L_{s1}}i_{d1}-\frac{V_1}{L_{s1}}cos\theta_1 \qquad (7.1)$$

$$\frac{1}{\omega_s}\frac{d}{dt}i_{q1} = -\frac{K_1 dc}{L_s}\sin(\alpha_1+\theta_1)-\frac{R_{s1}}{L_{s1}}i_{q1}-\frac{\omega}{\omega_s}i_{d1}-\frac{V_1}{L_{s1}}sin\theta_1 \qquad (7.2)$$

$$\frac{1}{\omega_s}\frac{d}{dt}i_{d2} = -\frac{R_{s2}}{L_{s2}}i_{d2}+\frac{\omega}{\omega_s}i_{q2}-\frac{k_2}{L_{s2}}\cos(\alpha_2+\theta_2)V_{dc}-\frac{1}{L_{s2}}(V_2 sin\theta_2 - V_1 sin\theta_1) \qquad (7.3)$$

$$\frac{1}{\omega_s}\frac{d}{dt}i_{q2} = -\frac{R_{s2}}{L_{s2}}i_{d2}+\frac{\omega}{\omega_s}i_{q2}+\frac{k_2}{L_{s2}}\sin(\alpha_2+\theta_1)V_{dc}-\frac{1}{L_{s2}}(V_2 sin\theta_2 - V_1 sin\theta_2) \qquad (7.4)$$

$$\frac{C}{\omega_s}\frac{d}{dt}V_{dc} = -k_1\cos(\alpha_1+\theta_1)i_{d1}-k_1\sin(\alpha_1+\theta_1)i_{q1}-k_2\cos(\alpha_2+\theta_1)i_{d2}-k_2\sin(\alpha_2+\theta_1)i_{q2}-\frac{V_{dc}}{R_{dc}} \quad (7.5)$$

Bus No. 1 (Power Balance Equation)

$$0 = V_1(i_{d1}-i_{d2})cos\theta_1 + \left(i_{q1}-i_{q2}\right)sin\theta_1 - V_1\sum_{j=1}^{n}V_jY_{1j}\cos\left(\theta_1-\theta_j-\emptyset_{1j}\right) \qquad (7.6)$$

$$0 = V_1(i_{d1}-i_{d2})sin\theta_1 - \left(i_{q1}-i_{q2}\right)cos\theta_1 - V_1\sum_{j=1}^{n}V_jY_{1j}\sin\left(\theta_1-\theta_j-\emptyset_{1j}\right) \qquad (7.7)$$

Bus No. 2 (Power Balance Equation)

$$0 = V_2\left(i_{d2}cos\theta_2 + i_{q2}sin\theta_2\right) - V_2\sum_{j=1}^{n}V_jY_{1j}\cos\left(\theta_2-\theta_j-\emptyset_{2j}\right) \qquad (7.8)$$

$$0 = V_2\left(i_{d2}sin\theta_2 + i_{q2}cos\theta_2\right) - V_2\sum_{j=1}^{n}V_jY_{1j}\sin(\theta_2-\theta_j-\emptyset_{2j}) \qquad (7.9)$$

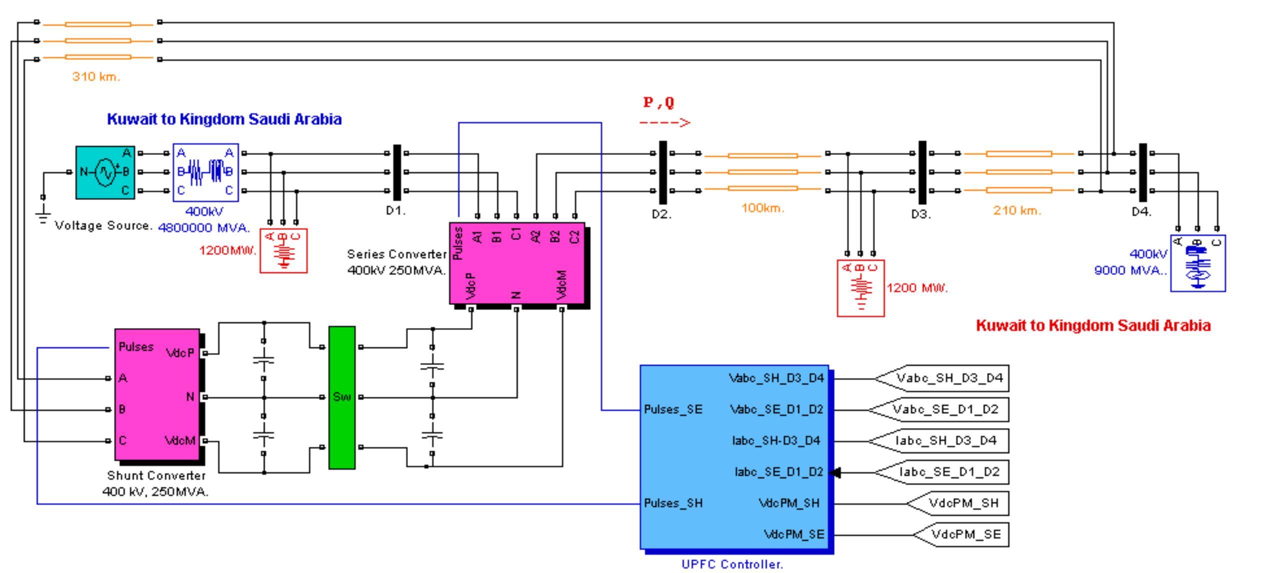


Figure 7-3: Simulated UPFC control schematic in between the Kingdom Saudi Arabia and Kuwait

7.1.3. Power system reinforcement plan in between the Kuwait and KSA:

Various analyses have been carried out to identify and determine the system requirements. In this study, recommendations have been provided against the findings to resolve system normal, single contingency and double contingency system problems in the downstream Kingdom of Saudi Arabia area. The comprehensive reinforcement plan for the Kingdom of Saudi Arabia area includes the following [5], [6]:

i) High capacity 10,000MVA, 400kV line in between Kuwait and Kingdom of Saudi Arabia stations
ii) A 500 MVA UPFC at the Kingdom of Saudi Arabia station fully utilize the high capacity of 400kV line to the GCC power grid, provide dynamic voltage support and control several mechanical switched capacitors in the area.
iii) Series reactors to constrain loading on existing thermal-limited facilities

7.1.4. UPFC model's distributed control

In the Appendix 7.A the introduced and demonstrated UPFC control model's three distributed control limits are minimum, medium and maximum control and operational deviation. These deviations are compensated at three operating limits by adjusting UPFC control device with corresponding P & I control values as stated in Appendix 7.A. The SSSC control device oscillates based on corresponding P & I value of each limit in between at +/-2%, +/-4% and +/-6% deviation at both sides of transmission lines to adjust reactive power compensation as required. These control boundaries customized P & I values which are enabling the control system to communicate each limit accurately and adjust the reactive power compensation based on sending and receiving ends voltage based deviations at different locations on the GCC power grid. These control boundaries will effectively operate when more than one FACTS device will be in operation at a different location on the GCC power grid. These will communicate to each other based on voltage, impedance, angle and power deviation at sending and receiving ends of the Kingdom Saudi Arabia and Kuwait power system facilities.

7.2. UPFC controller's selection process

The Wideband Delphi technique was used by incorporating various technical committees input to determine and develop prolific consensus to allot estimated values of significance and submission criteria(s) as demonstrated in Table 7.1. These 12^{th} areas input values are compiled and estimated based on UPFC control device operational significant. Table 7.2 indicates the estimated values of each FACTS device based on their operational and control capability in between the Kingdom Saudi Arabia and Kuwait that are obtained by using the Wideband Delphi Technique. Table 7.3 demonstrates the FACTS devices submission criteria to decide and select an appropriate control device. The equation (7.1) represents the calculation method to identify CRV_Z value of individual FACTS device based on their estimated statistical data as provided. Herein, CRV_Z model described its different parameters by the following equation [14].

$$CRV_Z = \sum_{n=1}^{12} \frac{B_n}{100} xCn = \left(\frac{B_1}{100} xC1 + \frac{B_2}{100} xC2 + \frac{B_3}{100} xC3 \ldots . + \frac{B_{12}}{100} xC12\right) \qquad (7.10)$$

Where:

Z(subscript) STATCOM, SSSC, UPFC, IPFC …..n

CRV_{UPFC} (credible value)

B_1 to B_{12} : indicates the Significant criteria as per Table 7.1)

C1 to C12: indicates the constant value of each device as shown in Table 7.2)

Final score of each device is indicated in Table 7.3

$CRV_{Z:}$ Indicates the calculated values of each device in Tables 7.5 & 7.6

Based on this calculation method each device CRV_Z value is derived and illustrated into Table 7.4 and 7.5. After successful evaluation, however, it was determined that the UPFC device obtained a high weighted score compared to others devices. Based on the results, this is a strong candidate to implement between the Kingdom Saudi Arab and Kuwait. Thus Wideband Delphi technique can be used effectively to develop prolific consensus to allot estimated values of significance and submission criteria(s) as demonstrated in Table 7.1 & 7.2. [14]. If summation score of table 7.4 and 7.5 of any device is above 65 it means good submission and 80 significant (strong candidate). Therefore, the Wideband Delphi technique has been given very prolific supporting results in order to formulate selection process of FACTS devices more pragmatically. This equation comprises of 12^{th} section corresponding to Table 7.1 as an input data from B1 to B12 this is also called the nominator and first part of the equation (7.10). These 12 areas total output value must be equal to 100. This is also called the denominator and second part of the equation (7.10). Third part of the equation is “C1 to C12” this is submission value of each segment of 12 areas as demonstrated into Table 7.2. During the calculation process the numerator is divided by the denominator and multiple with “C1 to C12” values in order to get final value of the each segment as indicated in Table 7.4. *(See section 5.2 for further details about the WBD)*

TABLE 7.1: UPFC DEVICE CRITERIA SIGNIFICANCE

S.No	Criteria	Weight (%)	S.No	Criteria	Weight (%)
1	Control Significance	13	7	Refuse disposal	6
2	Control Integration	12	8	Monitoring equipment	6
3	Design Capacity	8	9	Simulation results	6
4	Reliability	10	10	Capex	8
5	Maintenance frequency	11	11	Opex	8
6	Availability for field trial	6	12	Post Installation Support	6
			Total		100

TABLE 7.2: UPFC DEVICE SUBMISSION CERITERIA SCOREBOARD

Criteria Description	:	Submission Score
No submission of any consequence	:	0
Some submission but unacceptably low	:	20
Satisfactory	:	50
Good submission	:	65
Significantly above the minimum acceptable. Considered a strong candidate.	:	80
Exceptional submission		100

TABLE 7.3: UPFC DEVICE ESTIMATED SCORE

Device	Submission Score	Device	Submission Score
TCVR	48	STATCOM	69
TCPAR	51	SVC	57
UPFC	75	GCSC	42
IPFC	61	TSSC	40
SSSC	70	TCSC	44

TABLE 7.4: CALCULATED SCORE BY USING EQUATION 7.10

Criteria	$B_{1...12}$	$C_{1...12}$	Equation (5.8)	Weighted Score
Control Significance	13	70	$(B_1/100).C_1$	9.1
Control Integration	12	71	$(B_2/100).C_2$	8.52
Design Capacity	8	72	$(B_3/100).C_3$	5.76
Reliability	10	80	$(B_4/100).C_4$	8
Maintenance frequency	11	70	$(B_5/100).C_5$	7.7
Availability for trial	6	75	$(B_6/100).C_6$	4.5
Refuse disposal	6	83	$(B_7/100).C_7$	5
Monitoring equipment	6	83	$(B_8/100).C_8$	5
Simulation results	6	77	$(B_9/100).C_9$	4.62
Capex	8	72	$(B_{10}/100).C_{10}$	5.76
Opex	8	70	$(B_{11}/100).C_{11}$	5.6
Post Installation Support	6	92	$(B_{12}/100).C_{12}$	5.5
Total	100	-	-	75.06

TABLE 7.5: UPFC DEVICE CALCULATED SCORE AGAINST THE OTHER DEVICES

Static Shunt Compensator			Static Series Compensator		
STATCOM		SVC	GCSC	TSSC	SSSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	8.97	7.41	5.46	4.94	8.84
2	8.28	6.84	5.04	4.62	8.22
3	5.52	4.56	3.36	3.12	5.52
4	6.9	5.7	4.2	3.95	6.95
5	7.59	6.27	4.62	4.4	7.7
6	4.5	3.42	3.5	3.5	4.23
7	4.5	3.8	3	3.5	4.26
8	4.5	3.7	3	3.5	4.5
9	4.5	4	3	4	5
10	6	4.56	3.5	4.5	6
11	5.6	4.56	3.6	3.5	6.5
12	4.14	4	2.58	3.5	5.5
Total	71.00	59	45.00	47.05	73.38

TABLE 7.6: UPFC DEVICE CALCULATED SCORE AGAINST THE OTHER DEVICES

Static voltage and phase Angle control			Combined Compensator		Static Series Compensator
TCVR		TCPAR	UPFC	IPFC	TCSC
S.No	Weighted Score	Weighted Score	Weighted Score	Weighted Score	Weighted Score
1	5.85	6.5	9.1	7.8	5.59
2	5.46	6.03	8.52	7.23	5.19
3	3.68	4.04	5.76	4.84	3.48
4	4.65	5.08	8	6.08	4.38
5	5.17	5.61	7.7	6.71	4.84
6	2.85	3.85	4.5	3.68	2.66
7	2.88	3.09	5	3.69	2.67
8	2.91	3.5	5	4	3.5
9	2.94	3,5	4.62	4	3
10	3.96	5.5	5.76	5.5	3.62
11	4	5.8	5.6	5	3.64
12	3.85	6	5.5	4.5	2.75
Total	48.38	55.19	75.06	63.19	45.19

TABLE 7.7: DEFINED POWER AND SYSTEM'S VOLTAGE

Country ID	Country Name	Power ID	Mw	Voltage ID	Line Voltage kV
C1	Kuwait	PC1	1200	V1	400
C2	Saudi Arabia	PC2	1200	V2	400
C3	Bahrain	PC3	600	V3	400
C4	Qatar	PC4	750	V4	400
C5	Oman	PC5	400	V5	220
C6	United Arab Emirates	PC6	900	V6	400
C6	United Arab Emirates	PC7	400	V7	220

7.3. UPFC model operational strategy:

7.3.1. Voltage control:

During system disturbances, mechanically switched shunt capacitor banks and associated control are generally slow to react, whereas it offered a vulnerable control. To resolve such a situation, UPFC offered predetermined a reactive power margin to maximize the shunt converter's dynamic reactive power reserve for system contingency conditions. However, it ensures that the controllable reactive power range of shunt converter from (-250 to +250 Mvar) i.e. a maximum control range of 500MVar is available at all times to compensate for dynamic system disturbances [44], [45].

7.3.2. Power flow control:

With the system facilities at the Kingdom of Saudi Arabia station, the 400kV line loading is to be maintained at a level that would minimize the system losses. The study indicates that during peak or near peak load conditions a 1200 MW line loading will minimize the losses. The UPFC therefore is required to reduce the line loading by injecting reactive power. Hence reactive power flow and directions are monitored to maintain the dynamic reactive power margin of the shunt inverter. Series power flow control becomes more important during contingency conditions. Under severe contingency conditions, the UPFC controlled Kingdom of Saudi Arabia station line will be capable of transferring 1200 MW [47], [48].

7.3.3. Description of the UPFC circuit:

Table 7.8, 7.9, & 7.10 indicates the UPFC input data that is used to develop and simulate the UPFC device between KSA and Kuwait. The UPFC controller for the Kingdom of Saudi Arabia station was designed to meet the above mentioned system requirements, to provide fast reactive shunt compensation with a total control range of +/-500MVAR and control the power flow in the 400kV high capacity transmission line, forcing the transmitted power under contingency conditions up to 1200 MW. In order to increase the system reliability and provide flexibility for future system changes, the UPFC controller has to be configured in such way to allow self-sufficient operations of the shunt converter as an independent STATCOM and series converter as an independent Static Synchronous Compensator. These converters can be coupled to deliver either shunt only or series only compensation over a double-control range. Effectively, the actual control algorithms that govern the instantaneous operations of both converters are performed in the real-time control that employs multiple digital signal processors. The real time controller communicates the pole via the valve interface.

TABLE 7.8: POWER, VOLTAGE AND FREQUENCEY

Countries	Power Exchange, Voltage & Frequency
Power exchanged from Kuwait to main transmission line	1200MW, 400kV, 50Hz
Power exchanged from Kingdom Saudi Arabia to main transmission line	1200MW, 400kV, 60Hz DC link to convert 60Hz to 50 Hz frequency

TABLE 7.9: EXISTING REACTIVE POWER AND DISTANCE

Existing Power System	Reactive Power	Distance
Reactive Power Demand in the KSA (Al-Ghunan substation)	500Mvar	KSA (Al Fadhili substation to Al-Ghunan Substation) within KSA =114 KM
Reactive Power Demand in the Bahrian (Al Jasra substation)	850Mvar	KSA (Al-Ghunan Substation to Slawa substation) in the (Qatar) = 288KM
Reactive Power demand in the KSA (Al-Salwa Substation)	500Mvar	Qatar (Slawa Substation to Doha South Substation) within Qatar = 97KM
Reactive Power demand in the Qatar (Doha South Substation)	250Mvar	Qatar (Slawa Substation)

TABLE 7.10: MULTIVARIABLE CONTROLLER'S CONFIGURATION OF THE UPFC

UPFC LOCATION: connected at Al-Fadhili substation in between KSA and Kuwait	Iq regulator: Kp: 10 dB; Ki 34 dB	CC3 and LC3= minimum compensation capacitive or inductive (VC voltage change from 0 to 3.5%)
Rated UPFC: +/- 500 MVAR	DC balance regulator ; Kp: 0.0017 dB; Ki:0.017 dB Ref_V: 1.0 pu (400kV)	CC33 and LC33 = medium compensation capacitive or inductive (VC voltage change from 3.5 to 7.0%)
P (proportional gain) = 0.55 and 1.32 I(integral time) = 0.65, 0.85, 0.95, 1.01, 1.15 D (derivative time) None	Droop: 0.033 pu/100MVA; Kp:15dB; Ki: 3400/3600 dB	CC333 and LC333 = full compensation capacitive or inductive (VC voltage change from 7.0 to 10%)

7.4. UPFC operating performance:

7.4.1. Case 1: UPFC changing real power (p):

In this case the UPFC indicates zero injected voltage and the real power flow on the line near the "natural" 1200 MW from Kuwait Station as indicated in Figure 7-4. The shunt converter is regulating the Kingdom of Saudi Arabia bus to 1.0 pu by generating required reactive power to the power transmission system. The prime objective for this case is to maintain the Kingdom of Saudi Arabia bus voltage and line Q unchanged while there are big step changes in the line real power. The UPFC is firstly controlled to raise the line power to 1200 MW by injecting a voltage of about 0.78 pu in quadrature (lagging) with the Kingdom of Saudi Arabia bus voltage. In the meantime to satisfy the required conditions, the shunt converter drops capacitive output to about 90 Mavr and the series converter delivers 160MVar capacitive to the line [60].

7.4.2. Case 2: UPFC changing reactive power (Q):

The main objective of this control is to adjust the Kingdom of Saudi Arabia bus voltage at 1.0pu and keep the line real power, (p) constant while causing large steps in the line reactive power, Q. In the first swing the UPFC reference Q is changed from +250 Mvar to -250Mvar as indicated in Figure 7-4. After observing, 200Mvar is being received from the line compared with the 200Mvar delivered to the line initially. The UPFC forces the change by injecting about 0.05 pu voltage roughly in anti-phase with V_1. The line voltage V_2 is as a result reduced in magnitude by about 4.5%. In the second step, the Q reference is taken to +500 Mvar (500Mvar to the line). In this time the injected voltage is in phase with V_1 so that V_2 is increased by 4.5%. The final step reduces the Q reference to zero [23],[24].

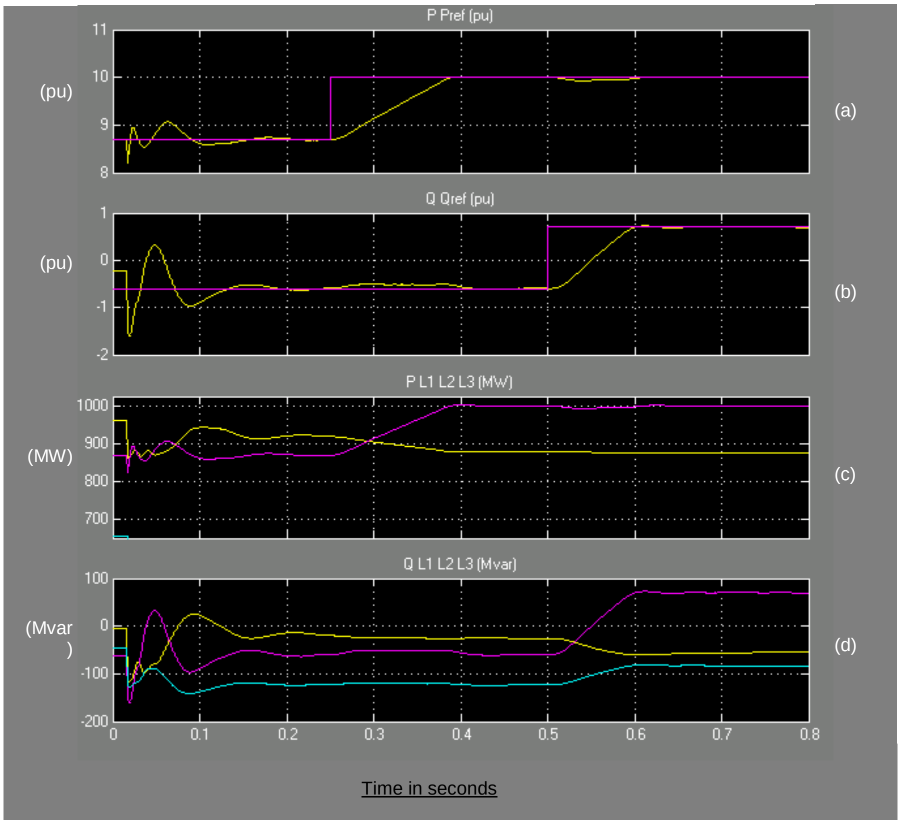


Figure 7-4: UPFC control operations (a) measured and reference power (b) measured and reference reactive power (d) three phases real power (f) three phases reactive power

7.4.3. Case 3: changing local bus voltage:

Figure 7-4 indicates the local bus voltage reference is stepped from an initial value of 0.95 pu to 1.05 pu and back to 0.95. The UPFC successfully holds the line P and Q constant (using very small changes in injected voltage). While the shunt converter goes from initially output of 120 Mvar to 220Mvar capacitive to 0 Mvar and back to 120 Mvar.

7.4.4. Case 4: UPFC holding unity power factor:

It is very interesting to drive a line at unity power factor, which makes it possible to deliver the largest amount of real power into the line for the lowest current. This should result in the most efficient use of the line from a thermal point of view.

7.4.5. Case 5: series converter operating in SSSC mode:

Figure 7-8 indicates the series converter injects into the line essentially in a quadrature with the prevailing line current. The injection angle deviates from true quadrature to draw real power from the line for converter losses to charge and discharge the DC bus capacitor bank. By means of the quadrature voltage injection, the SSSC is able to raise or lower the line current. But it cannot independently alter the P & Q.

7.5. Effectiveness of UPFC

7.5.1. GCC network performance without UPFC:

Figure 7-5 indicates the results without UPFC device operations, in the first trace there is variation of P against Pref observed, the Pref was 8pu and stayed the same for long because dynamic compensation is not available. In the second trace there is no variation of Q against Qref observed, the Qref was and stayed there for the rest of the operations. In the last two traces variation of reactive (Mvar) and active power (MW) at each line was not observed.

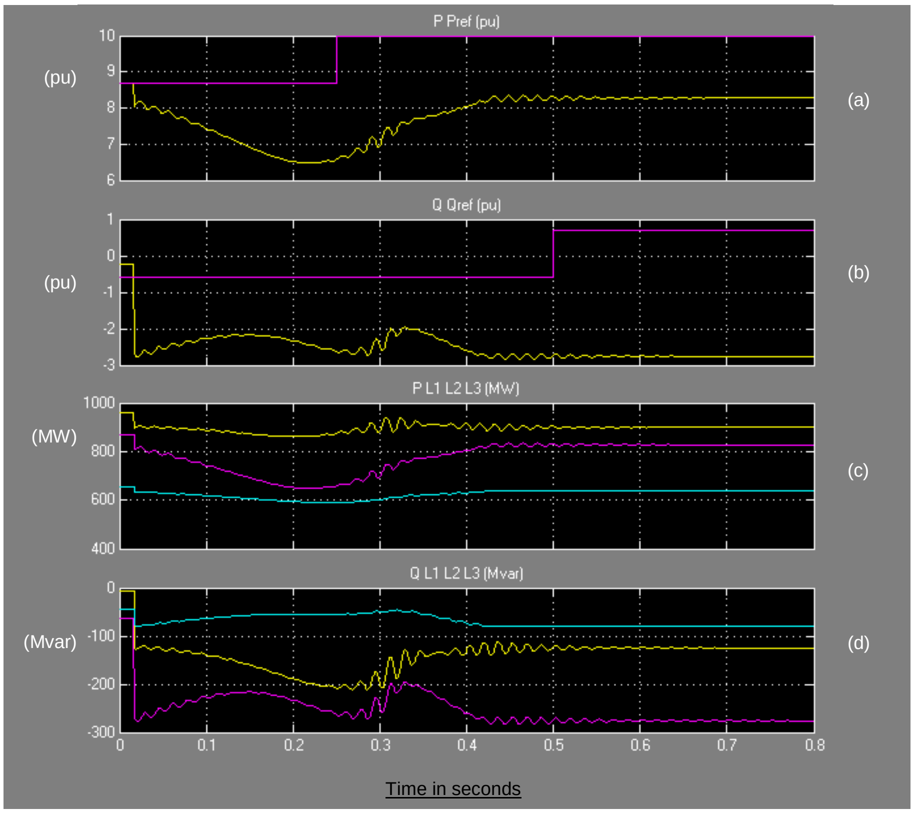


Figure 7-5: Network Operational trends without UPFC (a) measured and reference power in between KSA and Kuwait (b) measured and reference reactive power KSA and Kuwait (c) three phases real power (d) three phases reactive power

Figure7-6 indicates the first waveform of the UPFC shows measured power (yellow trace) against the reference power (magenta trace). Initially active power was 9pu from 0.1s to 0.25s and gradually ramped up to 12pu from 0.26 to 0.5s and stayed there rest of the operations. The second waveform of the UPFC shows the measure reactive power (yellow trace) against the reference reactive power (Magenta trace). Initially reactive power was zero from 0.1s to 0.5s against the reference value. It ramped up from 0 to 2pu from 0.5s to 0.65s against the reference value and it was stayed there rest of the operations. The third waveform indicates the L1, L2 and L3 real power variation; it was steady from 0.1 to 0.25s and ramped up from 0.27 to 0.5 from KSA to Kuwait. The fourth waveform indicates the L1, L2 and L3 reactive power variation it was steady from 0.1 to 0.55s and ramped up from 0.57 to 0.65 from KSA to Kuwait.

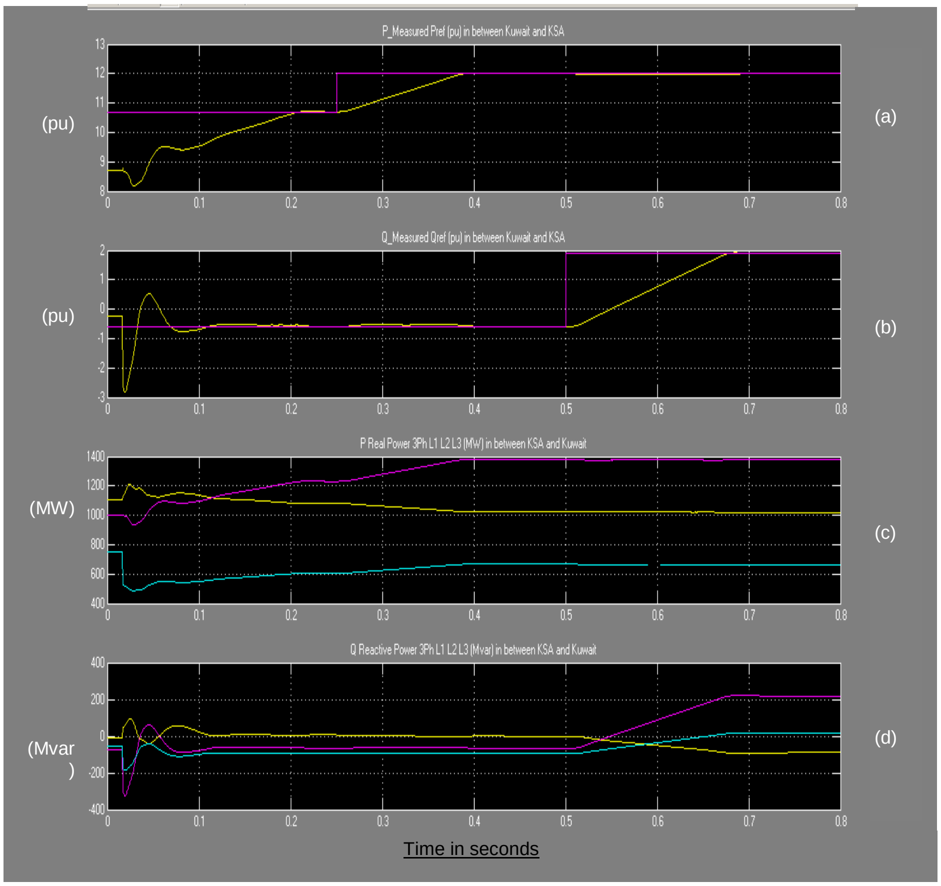


Figure 7-6: Network Operational trends with UPFC (a) measured and reference power in between KSA and Kuwait (b) measured and reference reactive power KSA and Kuwait (c) three phases real power (d) three phases reactive power

7.5.2. Network performance with UPFC:

7.5.2.1. Shunt part of UPFC:

Figure 7-7 is demonstrating the STATCOM operations results in UPFC, in the first trace there is variation of Vs and Vp voltage at coupling transformer, but significant change observed in Ip primary side current in following pattern (0.5pu to -0.5pu), (0.2pu to -0.2pu), and (1.0pu to -1.0pu). In the second trace variation in the Vdc voltage observed, it spiked from 0.001 to 0.1 second dropped at 20kV for 0.55 seconds and rise up to 22kV and stayed there to continue rest of operations. In the third trace variation in Q_ measure and Q_ ref observed. The Q_ measure shows variation from -0.35pu to -1.0pu and again oscillated after 0.5 seconds as reactive power demand increased from -0.35pu to 0.85pu and stayed there to continue the rest of the operations. In the last trace, variation in Vref against V_ measure observed, the V_ measure shows spike 1.01pu within 0.1 second and dropped at 0.99pu in 0.5 second and stayed there to continue the rest of the operations [62].

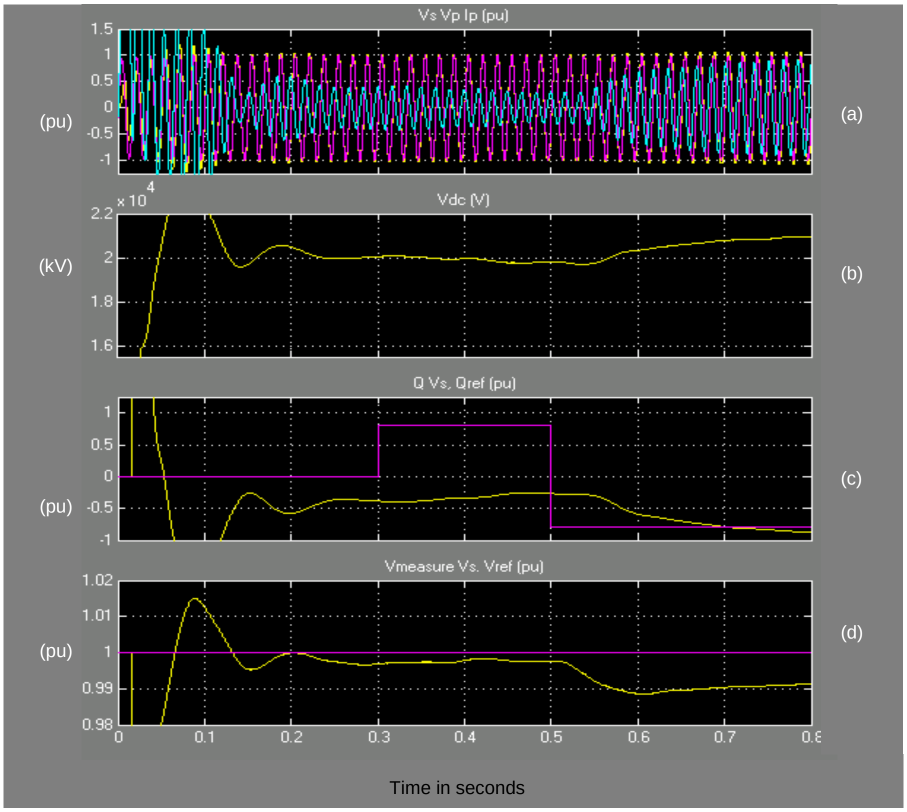


Figure 7-7: Shunt part of UPFC control parameters (a) primary and secondary voltage and current (b) measured value of DC voltage (c) measured and reference reactive power (d) measured and reference voltage

7.5.2.2. Series part of UPFC:

Figure 7-8 is showing the SSSC operations results in UPFC, in the first trace there is variation of V_{inj} voltage injected in series, the magnitude was -0.03 to 0.03 for 0.25 seconds and gradually increased up to -0.08pu to 0.08pu, and then stayed at -0.07 to 0.07 to continue the rest of the operations. In the second trace variation in Iabc observed, there is small slight dent (0.85pu-0.85pu) for 0.1 to 0.3 second and rise up (0.105pu to -0.105pu) for 0.3 to 0.5 and then dropped at (10pu to -10pu) stayed there for rest of the operations. In the third trace variation of Mag _Vinj and Vref observed, the Vref changed from 0pu to 0.75pu for 0.1 to 0.3 second and stayed there for the rest of the operations. Similarly, Vinj varied from 0pu to 0.04pu for 0.1 to 0.3 second and stayed at 0.05pu rest of the operations. In the fourth trace Vdc voltage observed, it spiked up to 22kV for 0.001 to 0.1 second and dropped at 20kV and stayed there to continue the rest of the operations. In the last two traces variation of reactive (Mvar) and active power (MW) at each line was observed [24].

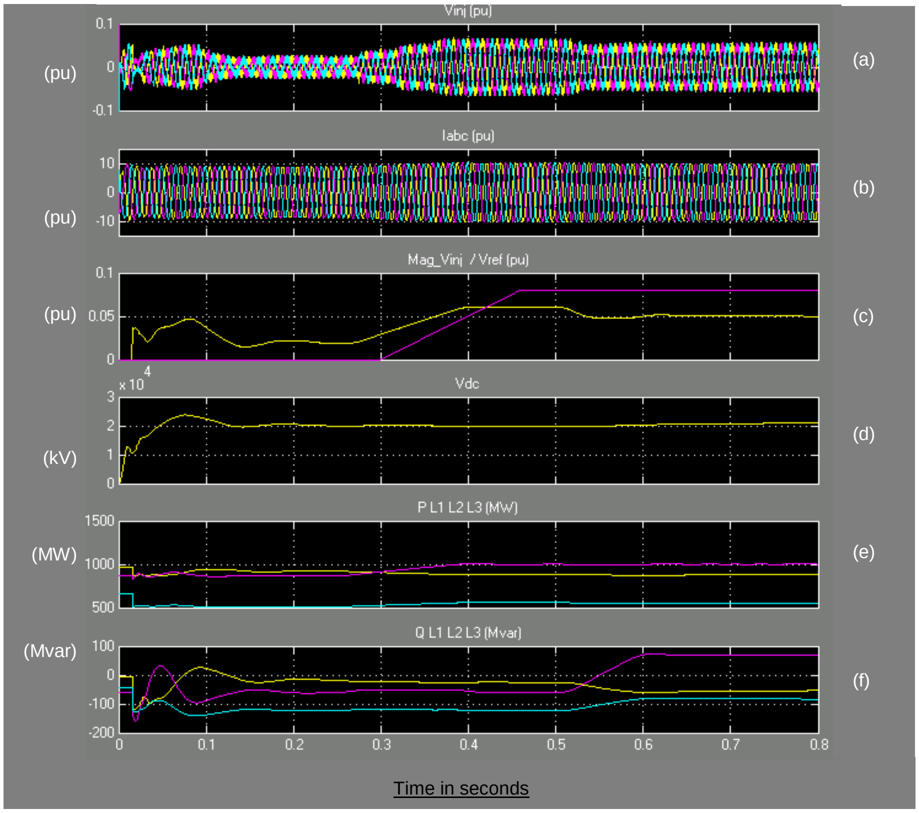


Figure 7-8: Series part of UPFC control parameters (a) injected voltage in series (b) three phases measured and reference current (c) measured and reference value of injected voltage (d) measured value of DC voltage (e) three phases real power (f) three phases reactive power

7.5.2.3. UPFC control device operations:

Figure 7-9 is indicating the UPFC operations results, in the first trace there is variation of P against Pref observed, the Pref was 8pu for 0.3 second and then increased to 10pu and stayed there for rest of the operations. Similarly, the P varied for 0.1 to 0.3 seconds and spiked up to 10pu to match with Pref and then stayed there to continue the rest of the operation. In the second trace there is variation of Q against Qref observed, the Qref was 0.5pu for 0.5 second and then increased to 0.8pu and stayed there for the rest of the operations. Similarly, the Q varied for 0.1 to 0.5 seconds and spiked up to 0.8pu to match with Qref and then stayed there to continue the rest of the operation. In the last two traces variation of reactive (Mvar) and active power (MW) at each line was observed [23].

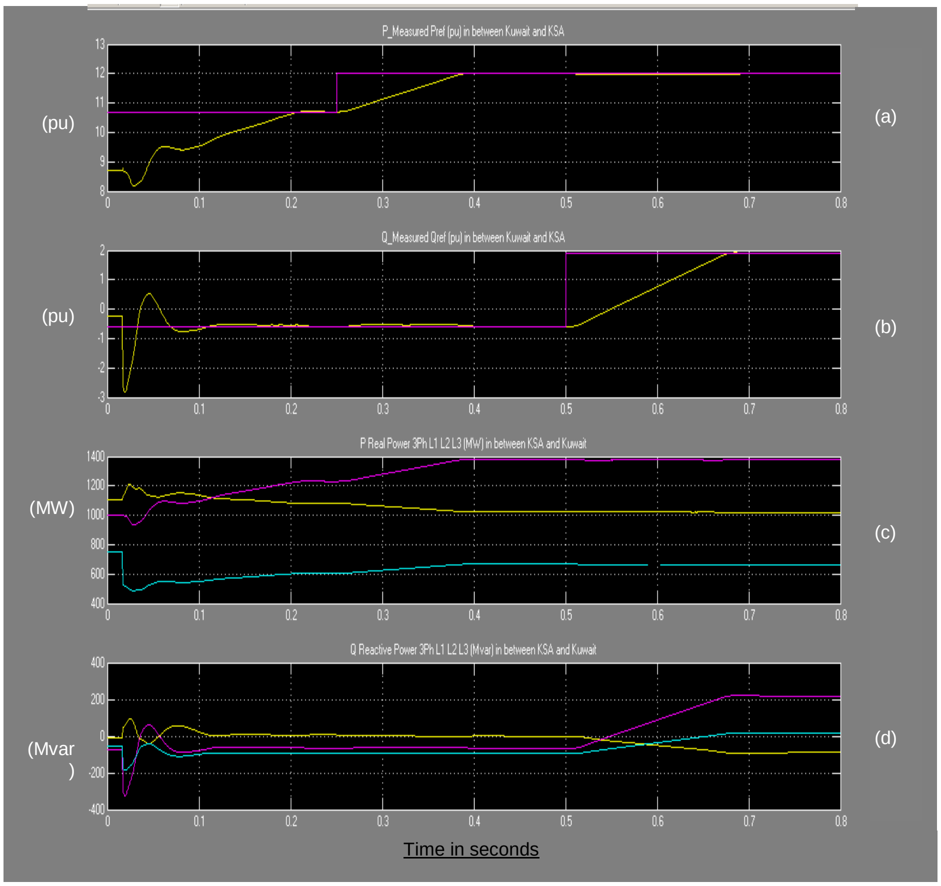


Figure 7-9: Network Operational trends with UPFC (a) measured and reference power in between KSA and Kuwait (b) measured and reference reactive power KSA and Kuwait (c) three phases real power (d) three phases reactive power

7.6. Results and discussion:

The UPFC control model has been configured by integrating three control limits that are defined to adjust to reactive power compensation: minimum, medium and maximum. These controlled limits are defined along with their corresponding PI control values in Appendix 7.A. Simulation results indicate that the UPFC controller will oscillate +/-2, 4 and 6% based on defined control limits to maintain reactive power compensation at both sides of the power transmission network. These control boundaries will communicate and adjust reactive power based on sending and receiving ends voltage deviation. The controller will oscillate and inject or absorb controlled reactive power based on corresponding PI controller values of each operating boundary as demonstrated in Appendix 7.A. These control boundaries will effectively operate when more than one FACTS device will be in operation at a different location on the GCC power grid in order to share 1200MW on the GCC power grid. These will communicate to each other based on voltage, impedance, angle and power deviation at the sending and receiving ends of the AC power system.

i) It has unique capability to provide independent and concurrent control for the real and reactive power flow, as well as regulation of bus voltage.

ii) It has a flexibility to run independently STATCOM and SSSC compensation, as well as for the regulation of bus voltage.

iii) The successful UPFC installation at the Kingdom of Saudi Arabia bus has also proven the concept of operating two or more voltage sources converters from a common dc bus, enabling the converters to exchange real power among them and thus being capable of providing two dimensional compensation by injecting real power as well as reactive power into the transmission line to validate its practical implementations.

7.7. Summary:

In this chapter, the UPFC device model demonstrates its strong impact voltage quality, power flow and power stability in order to share 1200MW power from the Kingdom Saudi Arabia and 1200MW power from the Kuwait power network on the GCC grid to meet industrial and domestic loads requirements at different atmospheric (summer/winter) operating conditions. Hereby the GCC power system background and viabilities are also addressed as well as the UPFC reinforcement plan. In addition to that, the UPFC control model new control optimization and device selection techniques are described in detail and its application in order to resolve various control and operational issues precisely.

Based on these control techniques three control limits along with corresponding PID new control values are incorporated into the UPFC model and simulated as demonstrated in appendix 7.A. These control techniques are providing a lot of confidence to operate the UPFC device independently or jointly (integrated) as further discussed in chapter 9. In this chapter the simulation results show the uniqueness of the UPFC. This model also demonstrates the pragmatic impact of the UPFC between Kuwait and the Kingdom of Saudi Arabia. The promising results demonstrated by the UPFC reveal the major practical advantages that can be obtained by this technology in order to implement in the GCC power grid. It has the unique capability to provide independent and synchronized control for the real and reactive power flow, as well as regulating the set bus voltage. It has a flexibility to run independently STATCOM and SSSC compensation and enhanced control to regulate the bus voltage. The successful installation of the UPFC device between Kuwait and the Kingdom of Saudi Arabia has also proven the concept of operating two or more voltage sources converters from a common dc bus, enabling the converters to exchange real power among them and thus being capable of providing two dimensional compensation by injecting real power as well as reactive power into the transmission line to validate its practical implementation.

CHAPTER 8

HVDC Implementation on the GCC power grid

8.1. Introduction

The Capacitor Commutated Converter (CCC) is a new type of HVDC converter topology which shows promising results for use in long-distance transmission lines. This technology is, thus, a potential candidate for use in HVDC transmission to deliver bulk power. The transmission line performance evaluations are presented using Matlab. The results demonstrate the superior performance of a CCC link, when connected to a very weak AC system in terms of increased transmission capacity and improved stability of the AC network on the GCC power grid. The following areas have been discussed in this chapter to implement HVDC on the GCC power grid.

A. HVDC design criteria
B. Design Studies review
C. HVDC Description
D. Rectifier operations
E. Inverter operations
F. HVDC equipments
G. HVDC Simulated model
H. Results/Discussion

8.2. Design criteria:

8.2.1. Transmission capacity:

A Bipolar DC link is rated for continuous power to transmit 1200MW (+/- 400kV 3000A) at the DC terminal rectifier converter station. HVDC can be operated in a bipolar or monploar mode with ground or metallic returns. The DC transmission system permits 120 minute over-laod of 1.1 pu of rated power without a redundant cooling system in service and up to 1.2 pu with a redundant cooling system [1], [2], [3].

8.2.2. System performance:

In order to ensure high-level system reliability and availability with minimal downtime, fast fault detection, effective repair and maintenance strategies as well as fault-tolerance control system and redundancy. The converter stations designs to loss 21-23 MW per station at 1200 MW power transmission. At rated transmission capacity the main loss sources are within the converter station's converter valves and transformers. Performance requirements for Dc system response, reactive power exchange with ac system, overvoltage control, ac voltage distortion equivalent disturbing current on the dc side, radio interference and audible noise have been considered in the system design [23].

8.3. Design studies

8.3.1. Design review:

The prime objective of design review is to analyze the required specification of the equipment, likewise main-circuit parameters, overvoltage, reactive power, insulation coordination, ac/dc filter performance and rating. And the second approach is to study the load flow and stability study, the sub synchronous resonance and ac equivalent study affect the stability control requirement of the interconnected ac/dc system [75].

8.3.2. Reactive Power management:

To meet reactive power requirements reactive power compensation elements have been designed to comply with the specified absorption and supply requirements, the specified maximum dynamic more than 2% ans steady state voltage after switching and maximum size of subbanks (300 Mvar for KSA and 340 Mvar Qatar side)

8.3.3. Overvoltage control:

To minimize overvoltage impact on ac a strategic controller has been designed. An overvoltage controller has been established to prevent the ac bus voltage exceeding the specified limits in order to protect the equipment and, at the same time, avoid unnecessary filter and shunt capacitor switching.

8.3.4. Insulation coordination:

Adequate correction of external insulation levels have been used to cover the impact of high altitude. With respect to the creepage distance, the design is based on the assumption of heavily polluted environmental conditions at both converter stations.

8.4. Main equipments and major technical features

8.4.1. Rectifier operations:

The rectifier mode of operations is demonstrated by the Alpha-min, constant I_d, VDCL, I_{min} characteristics.

1. **Alpha-min at rectifier**

Equation (8.1) denoted the converter theory

$$V_d = V_{dor} . \cos\alpha - R_{cr} . I_d \qquad (8.1)$$

Where $R_{cr} = \frac{3}{\pi} . \omega . L_{cr}$

Equation (8.1) indicates the AB straight line when V_d-I_d characteristics are plotted in steady state as demonstrated in Figure 8-1. This characteristics slope is the value of $-Rcr$ this is also called the commutation resistance. The low commutation resistance would involve a strong AC power system, and this characteristic would indicate almost horizontal line. If Id = 0 than this characteristic intercept at Vd axis which is equal to $Vdor\ Cos\alpha$. If the value of $\alpha = 0\ degs$ then maximum value of the Vd can be obtained and the rectifier is in theory diod converter. Practically, it has been identified that a minimum value $\alpha = 2 - 5\, degs$ this is an important to ensure that the converters valves have a minimum positive voltage to turning on their operations; the hatched areas indicate this characteristic at the rectifier operations as demonstrated in the Figure 8-1[23].

2. **Constant I_d at rectifier operations**

It has been identified and determined that the converter valves have limited thermal inertia which cannot carry large amount of current over their rated value for any extended period of time. The converter can carry a maximum I_{max} = 1.2 pu as the upper limit for the current carrying capacity of the converters valves. Figure 8.1 indicates the $Id = constant$ current "BC" straight line characteristic and its zone of operations.

3. **VDCL at rectifier operations**

If the AC power system voltage at the rectifier bus operations reduced due to some perturbation, the VDCL (Voltage-Dependent-Current-Limit) is a limitation forced by the AC power system to maintain the DC power flow. Figure (8.1) indicates that the system will utilize straight line DC' instead of slope line "CD" in order to improve the system sustainability.

4. **I_{min} at rectifier operations**

Current chopping phenomenal can be occurred due to any sort of discontinuous current operations with its sequential. This could lead the endanger DC voltage in the systemIn order to avoid such scenario **I_{min}** must be maintained in between 0.2-0.3 pu.

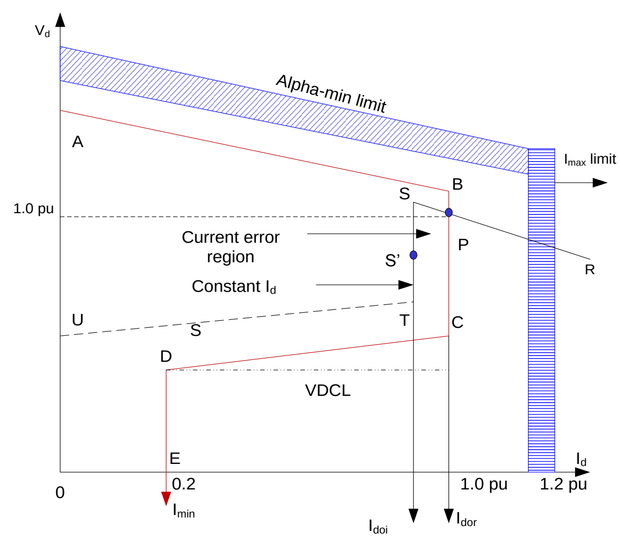


Figure 8-1: Static Vd- Id characteristics [3].

8.4.2. Inverter operations

The inverter mode of operations is demonstrated by the Gamma-min, constant current, Alpha-min, current error region characteristics.

1. **Gamma-min at inverter operations**

Equation (8.2) denoted the inverter theory of operations

$V_d = V_{doi}\,.\cos\gamma - R_{ci}.I_d$ (8.2)

Where $R_{ci} = \frac{3}{\pi}.\omega.L_{ci}$

Figure 8-1 indicates the SR line which defines the inverter operations and this is also called the constant extinction angle (CEA) control mode. The slope of this line defines the strength of the AC power system at inverter side. Herein, the minimum extinction angle (gamma) option is utilized normally in order to maintain seamless operations at inverter side.

2. Constant current at inverter operations

Figure 8-1 indicates the ST line which defines the constant current characteristics at the inverter. In order to maintain an exceptional and seamless operations of the DC link at cross-over point "P" line of the rectifier and inverter. The current margin in between inverter and converter should be $\Delta I_d = 0.1\,pu$ which can be expressed in equation (8.3).

$\Delta I_d = I_{dor} - I_{doi}$ (8.3)

Where: Current orders given: $(\text{rectifier})I_{dor}(inverter)I_{doi}$

The current demand by the inverter is less than the rectifier; therefore the margin typically maintained 0.1pu. In order to prevent current harmonics which may superimposed on the DC current, the magnitude of the current margin kept large which avoid rectifier and inverter constant current mode interaction. This is also called the current margin control method.

3. Alpha-min at inverter operations

Figure 8-1 indicates the TU line which defines the Alpha-min characteristics at the inverter side of operations. The $\alpha = 100 - 110\,degrees$ is maintained in order to limit the inverter into the rectifier operations even transiently. When I_d=0 the Alpha-min (100-110 degrees) value will ensure minimum dc voltage at the inverter for a fast start up of the DC link.

4. Current error region at inverter operations

In order to avoid any power system instability due to multiple operating points of the weak AC system at the inverter side a modification has been made often to the inverter characteristics of the PS' line in Figure 8-1 during the current margin period. This modification is illustrated in Figure 8-1a & b in this explanation VDCL characteristics are eliminated to make it simple. Firstly in rectifier operations two control modes are considered: alpha-min (line-AB) and constant current (line-BC). This mode of control is forced by the natural characteristics of the rectifier ac system and the converter valves which have an ability to operate at alpha angel equal to zero. In this limit the rectifier acts as diod rectifier. However a minimum positive voltage is required before firing the valves in order to ensure conduction so the $\alpha = 2 - 5\,degrees$ is normally forced. Secondly in inverter operations two control modes are considered: gamma-min (line-PQ) and constant current (line-QR). The cross-over point 'X' of the rectifier and inverter characteristics defines the operating point of the DC link. Furthermore, constant-current characteristics are also used at the inverter side of operations. The current demand by the inverter I_{di} is less than the rectifier I_{dc}; therefore the current margin ΔI typically maintained 0.1pu. In order to prevent current harmonics which may superimposed on the DC current, the magnitude of the current marginΔI kept large which avoid rectifier and inverter constant current mode interaction. This is also called the current margin control method [23].

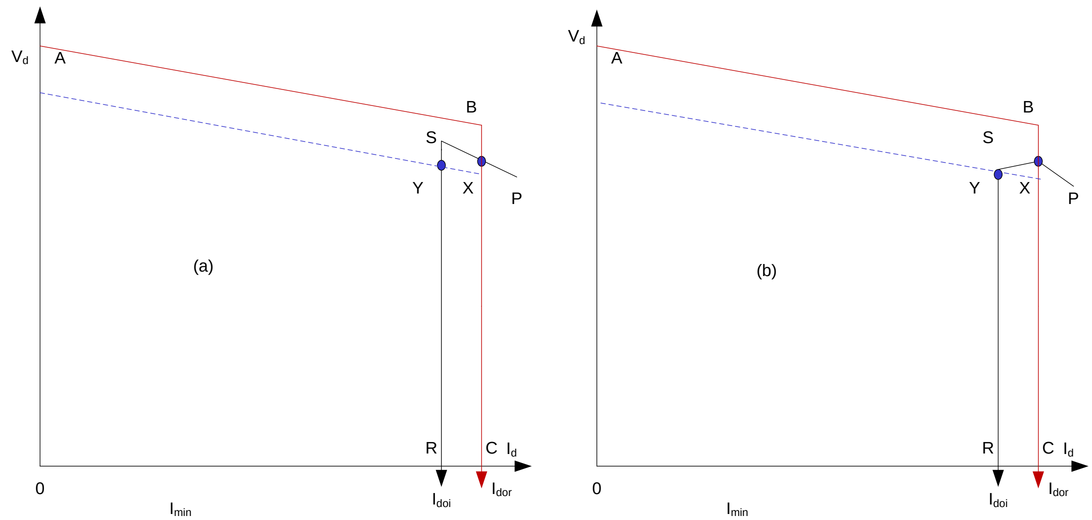


Figure 8-2: Static Vd- Id characteristics (a) unmodified (b) modified [3].

8.4.3. HVDC Equipment and Configuration

8.4.3.1 Smoothing reactor: The smooth reactors contain following configuration

- Inductance 270 mH
- Rated voltage: 500 kV
- Rated current 3000A
- Insulation level: 1550kV LIWL to ground
- Insulation level: 1675kV LIWL to terminal to terminal

8.4.3.2. AC breakers and DC switches:

In order to limit the inrush current from AC filter and converter transformer and related stress equipment the AC breaker must be equipped with synchronous switching. The equipment rating is based on maximum inrush without synchronous closing. MTRB metallic retune transfer breakers and metallic return switches are located in the DC yards. The converter stations are designed to allow the transfer ground return operations to metallic return and vice versa up to dc current 4kVa without interruption of transmission lines. Figure 8-3 indicates the principle arrange of MTRB.

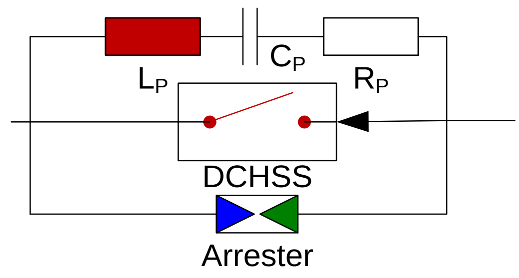


Figure 8-3: metallic return switch [3]

8.4.3.3. AC filters:

In order to meet the system performance requirements the compensation equipments comprises 3 A-type filters 4 B-type filter and 4-C-shunts introduces at KSA and 4 A-type filters 4 B-type filter and 5-C-shunts introduces at Qatar side. A triple tuned AC filter offers various advantages as indicated in Figure 8-4.

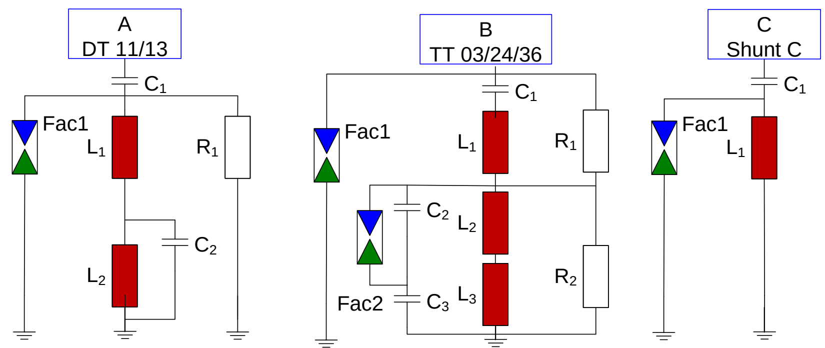


Figure 8-4: AC filter A,B, and C types [3]

8.4.3.4. DC filters:

Triple tuned DC filter are introduced to reduce the harmonic current in DC line. Due to triple tuned design a simple and redundant DC filter is used as indicated in Figure 8-5.

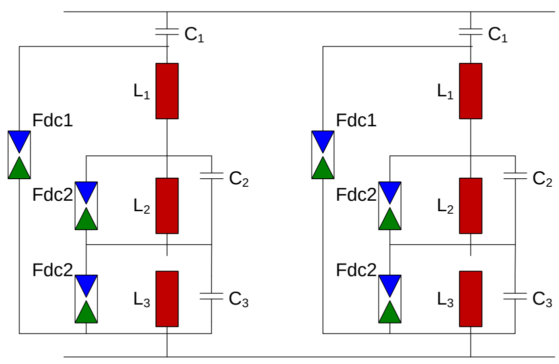


Figure 8-5: Triple tuned DC filters [3]

Table 8.1**:** Converter transformer data:

Segments	KSA	Qatar
Rated Power	1500 MVAR	1500 MVAR
Rated Voltage	400kV	400kV
Line winding	400/3	400/3
Leakage reactance	16%	15%
Tap changer	-5 to 20%	-7.5 to 20%
Step size	1.25%	1.25%
Insulation level (kV)	1550	1550

Table 8.2: Technical data:

Power rating	1200MW	Remarks
DC voltage	+/- 400 kV	
Overhead DC Transmission line length	800-1200 km	
Main reason for choosing HVDC	60/50 Hz and bulk power transfer	
Inverter stations	400 kV, 60 Hz, 1200 MW	
Inv. Side Controller gain Adjusted:	0.0054 dB	
Converter station	400kV 50 Hz 1200 MW	
Con. Side Controller gain Adjusted:	0.0065dB	

DC line voltage: 1pu=400kV and reference and measured current is 1pu=3KA A 1200 MW (+/-400 kV, 3kA, 60 Hz) DC interconnection is used to transmit power from a 400 kV, 1500 MVA, 60 Hz network to a 400 kV, 1500 MVA, 50 Hz network.

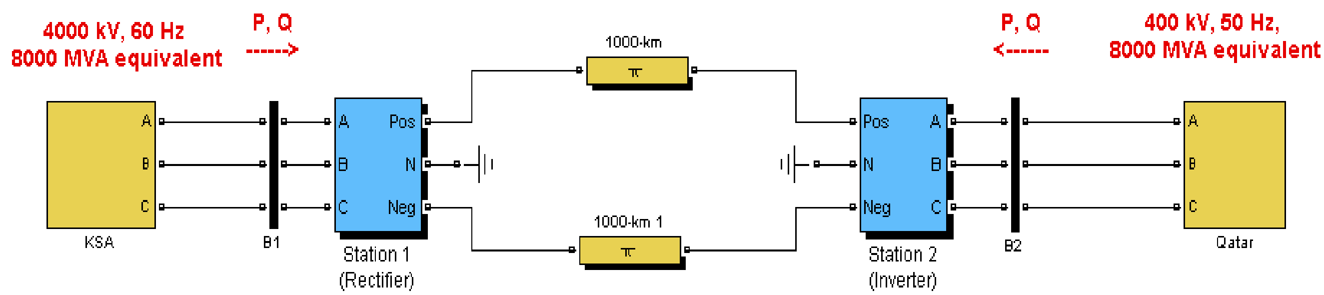


Figure 8-6: HVDC schematic investigated [Matlab]

8.5. HVDC model's circuit description:

The rectifier and the inverter are 12-pulse converters using two 6-pulse thyristor bridges connected in series. The rectifier and the inverter are interconnected through an 800 km distributed parameter line and two 0.5 H smoothing reactors. The transformer with fixed taps is assumed. Reactive power is required by the converters and is provided by a set of capacitor banks plus 11th, 13th and high pass filters for a total of 600 Mvar on each side. Two circuit breakers are used to apply faults on the inverter AC side and the rectifier DC side. DC Protection functions are implemented in each converter. At the rectifier the DC fault protection will detect and force the delay angle into the inverter region so as to extinguish the fault current. At the inverter the commutation failure prevention control will detect AC faults and reduce the maximum delay angle limit in order to decrease the risk of commutation failure. The Low AC voltage detection blocks will lock the DC fault protection when a drop in the AC voltage is detected. The Master Control block initiates the starting and stopping of the converters as well as the ramping up and down of the current references. The power system and the control system are both discretized for a sample time Ts=50 us [67].

8.5.1 Station No. 1 rectifier control Operations parameters:

8.5.1.1 AC side Power delivery trends:

Figure 8-7 indicates the 400 kV AC side voltage control as per defined specification. A control signal is generated to maintain 2pu line voltage within specifications. Through the précised power control loop the measured power was maintained as per reference power at a minimal fluctuation. There is a small fluctuation in the first cycle of rectifier operations. In the third trend, continuous reactive power is injected to meet the operations requirements. In the fourth three-phase voltages are shown in sinusoidal waveform as well as in line current.

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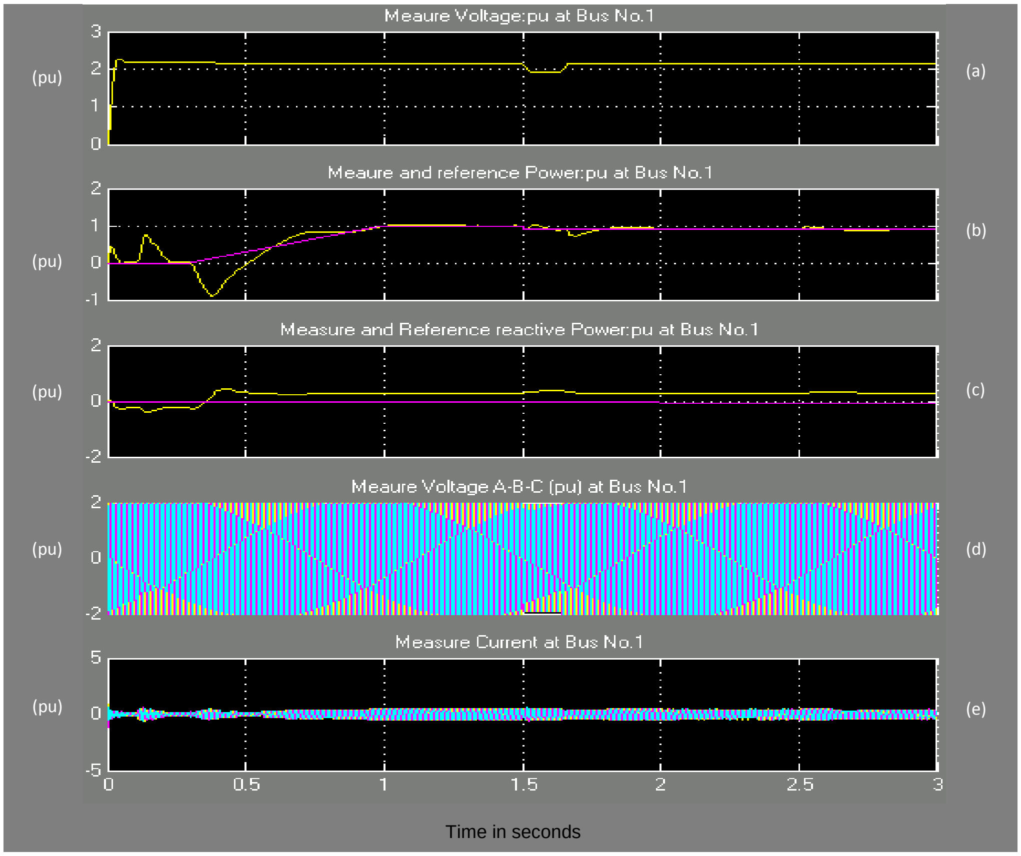

Figure 8-7: Control signal at Bus No.1 (a) measured voltage at Bus-1 (b) measured and reference power at Bus-1(c) measured and reference reactive reference power at Bus-1 (d) measured current at Bus-1

8.5.1.2 DC side Power delivery trends:

Figure 8-8 indicates the +/- 400 kV DC side voltage control as per defined specification. There is small variation in the DC control signal to maintain a certain level of DC voltage. Controller FDB control loop gain is calculated to minimize control signal fluctuation with a high degree of reliability. It has been also observed that there is a slight variation in DC power delivery. Further tuning is recommended to minimize the variation.

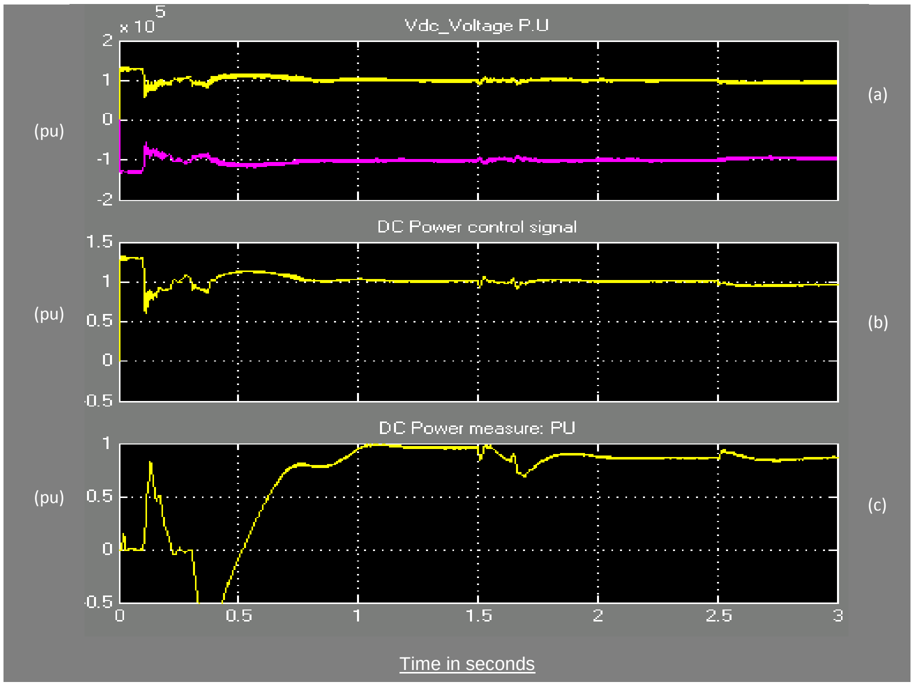

Figure 8-8: DC side voltage control (a) DC voltage at station-1 (b) DC power control signal at station-1 (c) DC power measured at station-1

8.5.1.3 DC voltage balanced control loop at station No. 1:

Figure 8-9 indicates a small fluctuation in control signal to balance DC voltage at the rectifier side. The control loop gain has been adjusted to meet rectifier operational requirements with a high degree of accuracy. It has been observed at nearly +/- 0.02 pu. Further investigation is still going on to improve existing control loop operations.

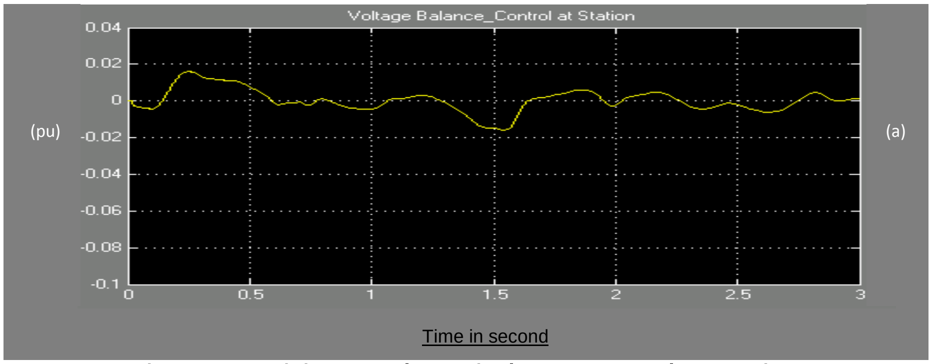

Figure 8-9: (a) DC voltage balance control at stations-1

8.5.2 Station No. 2 Inverter control operations parameters:

8.5.2.1 <u>AC side Power delivery trends:</u>

Figure 8-10 indicates the inverter operation to convert 400kV DC to 500kV AC side voltage control as per defined specification. A control signal is generated to maintain 2pu line voltage within specifications. Through the précised power control loop the measured power was maintained as per reference power at a minimal fluctuation. In the third trend, continuous reactive power is injected to meet the inverters operations requirements. In the fourth three-phase voltages are shown in sinusoidal waveform as well as line current.

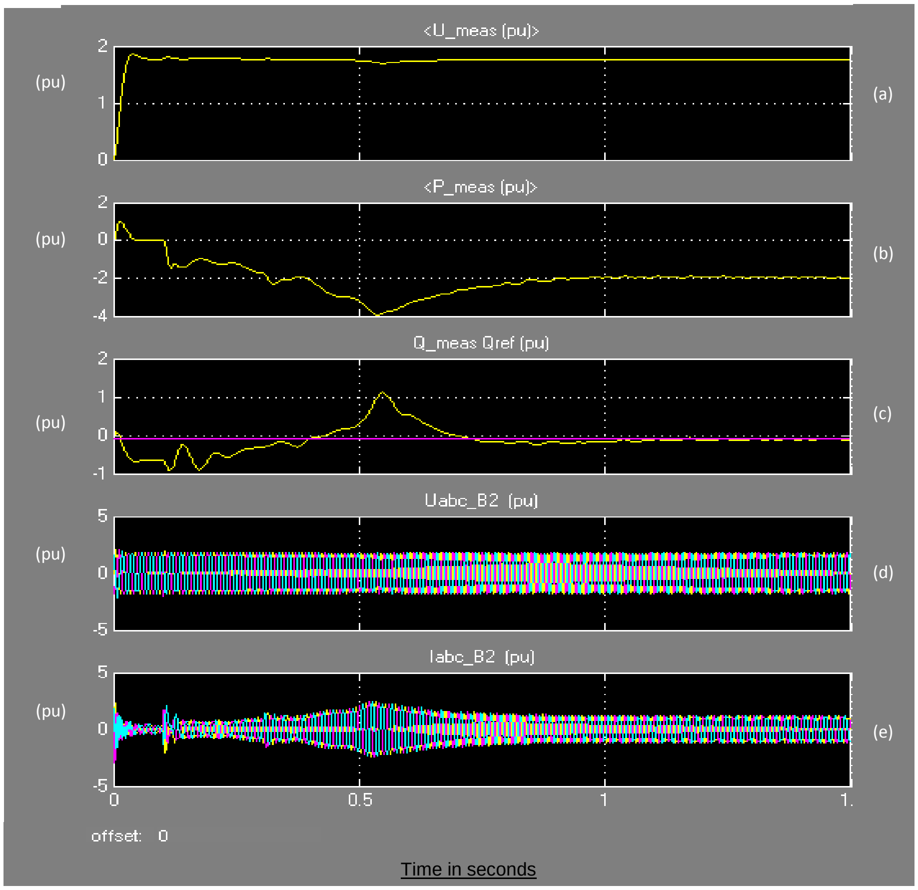

Figure 8-10: Control signal at Bus No.2 (a) measured voltage at Bus-2 (b) measured and reference power at Bus-2(c) measured and reference reactive reference power at Bus-2 (d) measured current at Bus-2

8.5.2.2 DC side Power delivery trends:

Figure 8-11 indicates the +/- 400kV DC side voltage control as per defined specification. There is negligible variation in the DC control signal to maintain a certain level of DC voltage. Controller FDB control loop gain is calculated to minimize control signal fluctuation with a high degree of accuracy. It has been also observed that there is a slight variation in DC power delivery. Further tuning is recommended to minimize the variation.

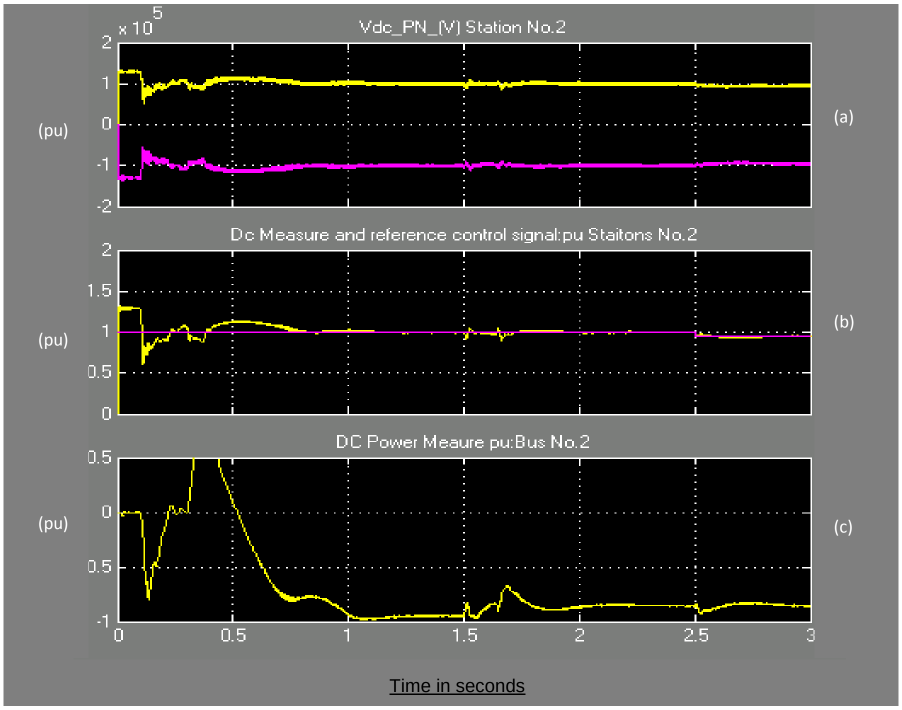

Figure 8-11: DC side voltage control (a) DC voltage at station-2 (b) DC power control signal at station-2 (c) DC power measured at station-2

8.5.2.3 DC voltage balanced control loop at station No. 2:

Figure 8-12 indicates small fluctuation in control signal to balance DC voltage at rectifier side. The control loop gain has been adjusted to meet rectifier operational requirements with a high degree of accuracy. It has been observed at nearly +/- 0.02 pu. Further investigation is still going on to improve existing control loop operations..

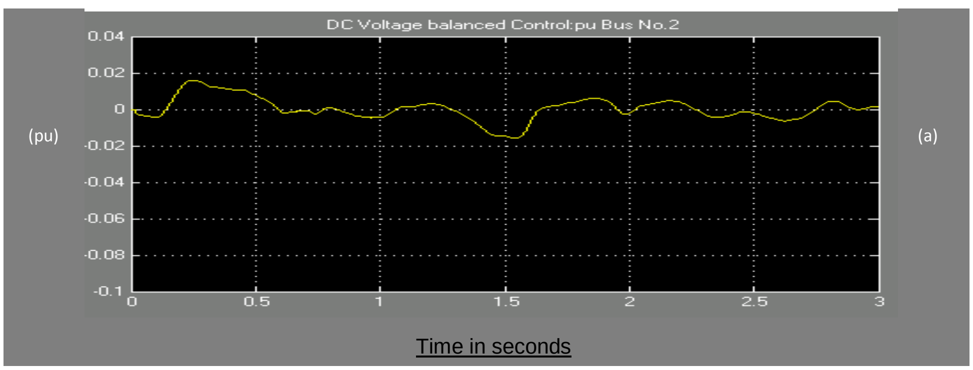

Figure 8-12: DC side voltage balanced control at station-2

8.6 Results and discussion:

The HVDC control model has been configured by integrating with STATCOM, SSSC & UPFC devices. By carrying out a careful study, it has been determined that the HVDC inform of back-to-back – STATCOM will add the value to the AC power system to regulate the power and modulation (power angle and voltage)**.** During this study, it was also identified that the KSA power facilities are operating at 60Hz and the rest of all the GCC countries are operating at 50Hz. Therefore back-to-back DC link has an instrumental approach to develop a communication link between the two frequencies: the KSA and the rest of the GCC countries. A study (studies) also indicates that the HVDC system is a very viable solution to deliver bulk power through a long transmission line from KSA to rest of the GCC power network. The supplied power system DC link has the capacity and capability to share 1200MW power on the GCC power network**.** This solution is also very economical and providing a well-controlled power transmission flow through the DC link. Principal drive of the HVDC model is to develop a program to identify and determine to transfer (1200MW, 400kV, 60 Hz) power from KSA generation to the GCC grid (400kV, 50Hz). A power system analysis shows the results that are very convincing, as anticipated, by using a power system simulation package that also evaluates the effect of compensation on the transmission line to obtain the following objectives:

- Identify and determine the required system frequency to maintain the system voltage.
- Identify and determine the maximum power transfer limit that may be transmitted under different conditions.
- Investigate the influence of various factors such as line length, load power factor and reactive power requirements to maintain maximum power transfer capability.

In general, various investigations have been carried-out to validate simulation technique and its results by sharing 1200MW power from the KSA power generation system on the GCC power network to meet industrial and domestic loads operational requirements at various atmospheric operating conditions. As a result, very much promising outcomes have been achieved during this study.

8.7 Summary:

The HVDC model demonstrates the impact on the GCC power grid in order to deliver 1200MW power from Saudi Arabia on the GCC power grid to meet industrial and domestic loads operational requirements at different atmospheric conditions. Hereby Power system transmission capacity, system reinforcement and design criteria have been addressed in this chapter by putting GCC Power grid security and operational criticalities into consideration. In addition to that, reactive power management, overvoltage control, insulation coordination as well as rectifiers and inverter operations are also described in this chapter. Furthermore, smoothing reactor, breakers, DC switches, harmonic (AC+ DC) filters technicalities are also addressed in detail.

CHAPTER 9

FACTS-FRAME Architecture to Integrate FACTS Devices on the GCC Power Grid

9.1. Introduction:

FACTS-FRAME encompassed various interconnected layers of control and operations in the GCC power grid. The first layer describes the geographical positions of the each GCC country. The second layer describes the geographical location of each FACTS device and their static and dynamic operational data requirements for application. The third layer describes the selection process of the required FACTS device based on its capability and capacity to overcome power transmission system's contingences on the GCC power grid. The fourth layer describes the communication interface to integrate STATCOM, SSSC and UPFC with each other. The fifth layer describes the control pattern of each FACTS device. These control patterns are configured to accelerate and de-accelerate converter(s) gating response based on each devices time-based capability and capacity to inject and absorb reactive power in capacitive or inductive modes of operation of the AC power system. A new technique was introduced and demonstrated to adjust reactive power compensation in three modes of operations (minimum, medium and maximum) based on vital operating and control parameters deviation. To maintain these three controls and operating boundaries the PI controller's response is configured and integrated to reduce or eliminate the operating and control deviation. If deviation is +/- 2% the controller will inject or absorb minimum reactive power for +/- 4% medium reactive power and for +/- 6% maximum reactive power. The simulation results indicate that this control technique has a great potential to enhance the FACTS control devices robustness and strong integration with a degree of precision.

Herein, large numbers of research papers and material are reviewed thoroughly related to the electrical power system control and operations at micro-level to produce high quality results as well as by putting in massive 18 years industrial experience in the field of instrumentation and control system engineering. Whereas, the last 18 years of instrumentation and control system engineering experience has been obtained practically by practicing and customizing different types of industrial applications in instrumentation and control systems, likewise DCS, SCADA and APCS control systems that are largely commissioned by the Honeywell, ABB and Yokogawa companies. The principal aim of this work is to customize FACTS control devices operational framework for multipurpose on the GCC power grid (Qatar, KSA, Oman, Bahrain, Kuwait and UAE). This framework architecture comprises of five layers of FACTS control devices (STATCOM, SSSC and UPFC) as demonstrated in Figure 9-2. This five-layer architecture is designed for its future growth and reusability so that more complex power system operational problems can be addressed within control architecture after its successful implementation.

These five of layers framework-architecture, named “FACTS-FRAME”, demonstrate how various FACTS devices control systems are communicating to with other and controlling various FACTS devices at different locations on the GCC power grid in order to address time based operational contingencies on the GCC power grid. The FACTS-FRAME is designed to handle complicated and distributed computation for intensive power system calculation and implementation on multiple power systems distributed networks. The FACTS-FRAME has the capacity and capability to identify and determine various complex power system problems which are persisting on the GCC power grid: poor voltage quality, poor load flow control, limited power transfer capacity and power system stability issues.

In order to address these issues steady state mathematical models have been derived by considering current operational and security criticalities in order to indentify and determine different operational and control scenarios on the GCC power grid. Distributed power flow algorithms have also been developed in order to understand and implement FACTS devices to get maximum benefits. Based on FACTS devices applications very promising results can be obtained by establishing integrated multiple FACTS devices FACTS-FRAME network on the GCC power grid. Listed below major benefits may be witnessed by developing and implementing strategic FACTS-FRAME on the GCC power grid [1],[2],[3].

a) Increasing power transfer capacity, controllability and operational reliability on the GCC power network.
b) Reducing new Line Construction and preserving the Environment on the GCC power network.
c) Enhancing power system operational stability, voltage control and addressing Retiring/aging Transmission Assets on the GCC power network.

Figure 9-1 illustrates a designed power exchange and also shows an inter-tie connection with STATCOM, SSSC & UPFC in between the GCC countries. Prime contributions of this research work are as listed below.

a) Investigate the impact of integrated FACTS devices (STATCOM, SSSC & UPFC) with new PI control parameters and its operating technique on the GCC power network.
b) Compare the power system network with and without FACTS devices (STATCOM, SSSC & UPFC) application at different locations on the GCC power network.

Successful implementation of the FACTS-FRAME will increase the network loadability and the enhanced voltage profile at different locations on the GCC power grid. The rest of this chapter is organized as follows. In section 9.2, 9.3 FACTS-FRAME system overview, FACTS FRAME architecture. In section 9.4, 9.5 FACTS FRAME configurations FACTS FRAME case study. In section 9.6 and 9.7 FACTS-FRAME effectiveness (observations) and results are presented.

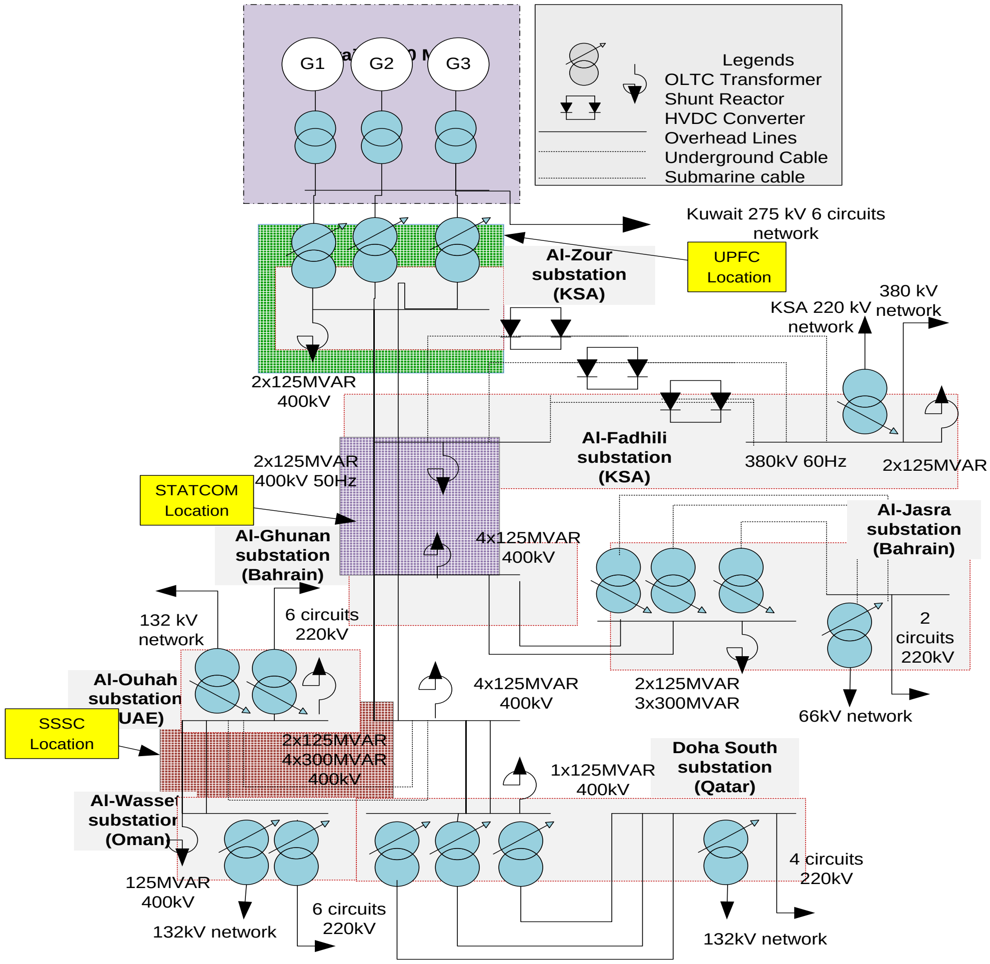

Figure 9-1: Proposed FACTS devices location on the GCC power grid

9.2. FACTS-FRAME system architecture

Figure 9-2 describes a proposed “FACTS-FRAME” architecture that was formulated in different types of multiple layers. This layered architecture has multi-proportional dependencies on each layer on a need’s analysis basis. This architecture layers are described as. **Primary layer**: describes the GCC countries existing control and operations philosophy. **Secondary layer**: describes FACTS devices control and operations philosophy and their viabilities and vulnerabilities. **Tertiary layer**: the GCC countries operational requirements or constraints and how these countries are communicating to each other in order to resolve any type of stalemate. **Quarternary layer:** describes FACTS-FRAME (interface with countries and multiple FACTS devices) and how these devices are communicating to each other in order to maintain line voltage and the required power exchange at different locations on the GCC countries more pragmatically. **Quinary layer:** describes the control topology of all devices, strategically, this layer also configured with internal control (de-centralized) and external control (centralized) topologies. Herein the term of layer describes the meaning of one complete package or unit, which is used to develop an individual model and its integration with other models that are in operation on the GCC power grid. These layers also indicate four-way dependency between the "packages".

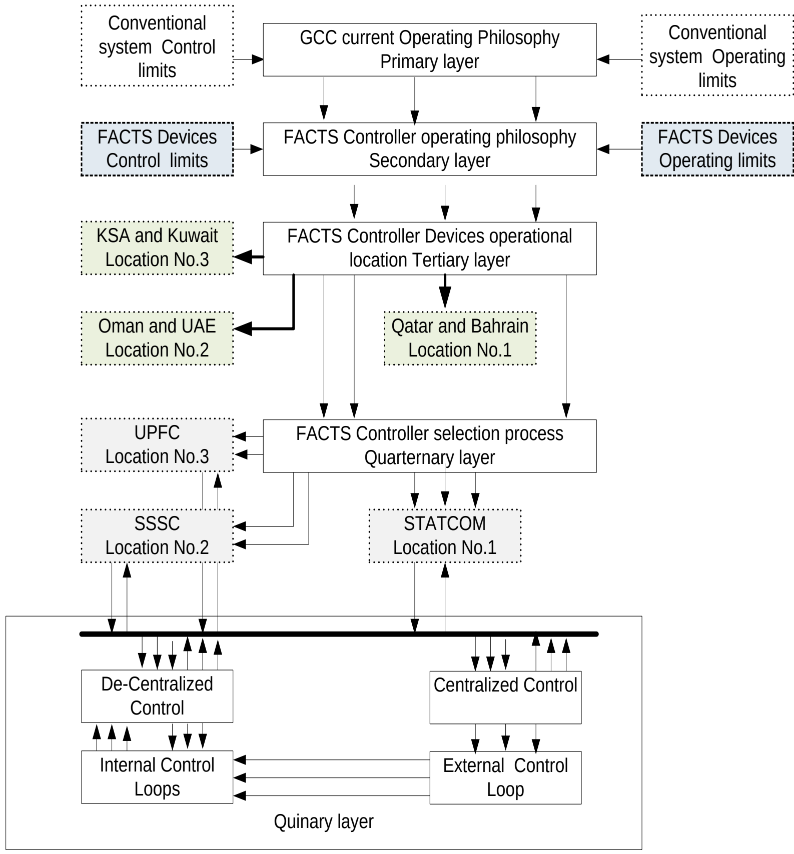

Figure 9-2: FACTS-FRAME Architecture

9.3. FACTS devices selection process

Refer to the chapter 5, 6, & 7 to know more about the Technology selection process by using Wideband Delphi technique.

9.4. FACTS devices optimal location:

9.4.1. Location no.1 most important load center (Qatar and Bahrain):

This is identified and determined through various techno-economic analyses on the GCC power grid that the FACTS devices are recommended to be installed near the load center to diminish the effect of grid disturbances on susceptible loads by putting all sorts of power system's operations criticalities into consideration. These disturbances could be short-circuit or loss of major power lines in one of the GCC countries. Hence, this location is strongly recommended for the STATCOM device implementation to serve the purpose as mentioned above. Based on these operating conditions the SVC was installed at the Sylling substation near the city of Oslo in Southern Norway and the STATOCM at the Sullivan substation of the Tennessee Valley in USA [1].

9.4.2. Location no.2 critical substation (Oman and United Arab Emirates):

This is identified and determined by carrying out various analyses and recommended against the findings. The FACTS devices must be installed near the critical substation in order to mitigate low voltage during active power swing as well as to prevent excessive under or overvoltage circumstances in the event of, if any, major power line or generation lost on the GCC power grid. Hence, this location is strongly recommended for the SSSC device implementation to serve the purpose as mentioned above. Based on these operating conditions the TCSC is installed at the Kayenta substation, northeast Arizona [1]

9.4.3. Location no.3 major industrial or traction load (Kuwait and KSA):

This is identified and determined that the FACTS devices are also recommended to be installed near the supply point of major industrial and other types of commercial loads in order to support temporary under or overvoltage conditions. These devices will also act as compensator in order to improve voltage quality on the GCC power grid whenever there is disturbance. Hence, this location is strongly recommended for UPFC device implementation to serve the purpose as mentioned above. Based on these operating conditions the UPFC is installed at the Inez substation AEP Kentucky USA. [44-58]

9.5. FACTS devices decentralized control (Local Control)

In Appendix 4-A introduced and investigated internal control loop of each the FACTS device (STATCOM, SSSC and UPFC). The internal control loop contains large numbers of measured parameters and their reference values to identify the deviation at different locations on the GCC power grid. These control loops are implemented independently to the STATCOM, SSSC and UPFC devices to adjust their control response at their defined locations as simulated and demonstrated in Figure 9-3 & 9-4 by using Matlab software. In the STATCOM internal control loop five control blocks are demonstrated, referenced and measured voltage control blocks, reference and measured current control blocks and measured power exchange control block of the each substation on the GCC power grid, where the device is implemented. These control blocks provide a composite control function based on the deviation to the final control element to adjust the converter gating pattern logic operations to inject or absorb the reactive power. The reference values of each control block can be manipulated by configuring control and operating limits and by dividing these devices' control and operational responses as discussed in section 9.9 and Table 9.7. In this model four internal control loop operators are introduced D5 &D6 (STATCOM), D8 & D9 (SSSC), UPFC (D1, D2-STATCOM and D3 & D4-SSSC) of each independent control loop. These operators indicate the control loop deviation (reference_voltage)–(measured_voltage) and (Iq-reference)–(measured-current) of the STATCOM, SSSC and UPFC based on the deviation convertor(s) gating operations can be accelerated or de-accelerated. These deviations are plugged in the final control block by incorporating three operating and control ranges +/- 2, +/-4, and +/-6% compensation factors. Based on these factors the control devices are customized to adjust the controllers' reactive power compensation. After defining and configuring, each control device response as discussed above, these controllers will adjust their convertor(s) gating logic pattern operations based on (D5 &D6), (D8 & D9), (D1 & D2) and (D3 & D4) operators' deviations and are being calculated during the simulation process individually and independently. This is also known as a de-centralized control system to control and monitor the device locally at their locations. The internal control system will be responsible for controlling the line voltage and power flow locally. This loop will also introduce two modes of operations' capacitive and inductive based on deviation to control each device locally. This is an integral part of the converter. The main function of this control loop is to operate the power switches to generate fundamental output voltage waveforms based on deviation as discussed above.

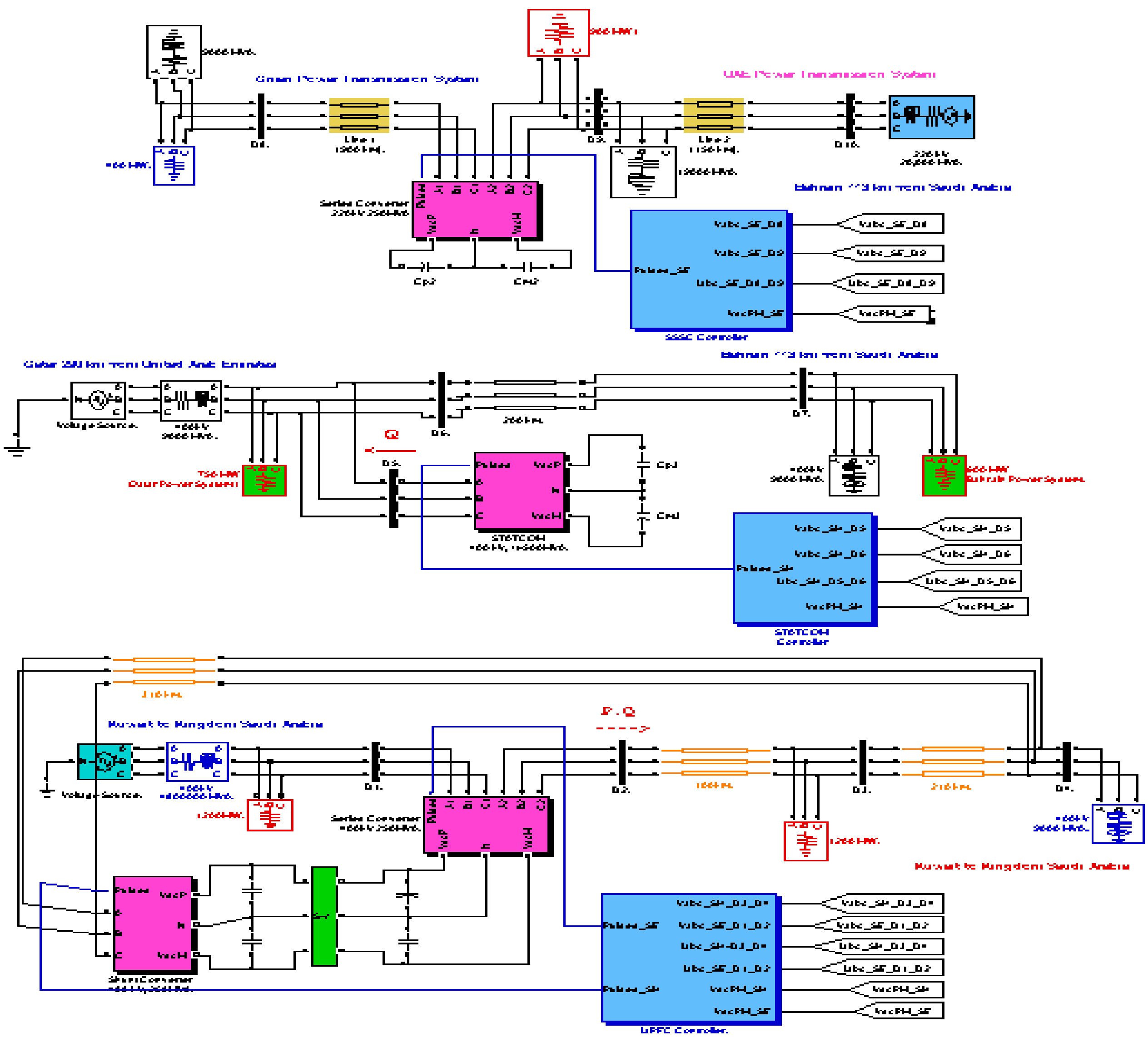

Figure 9-3: decentralized STATCOM, SSSC and UPFC control devices control topology on the GCC power grid [Matlab]

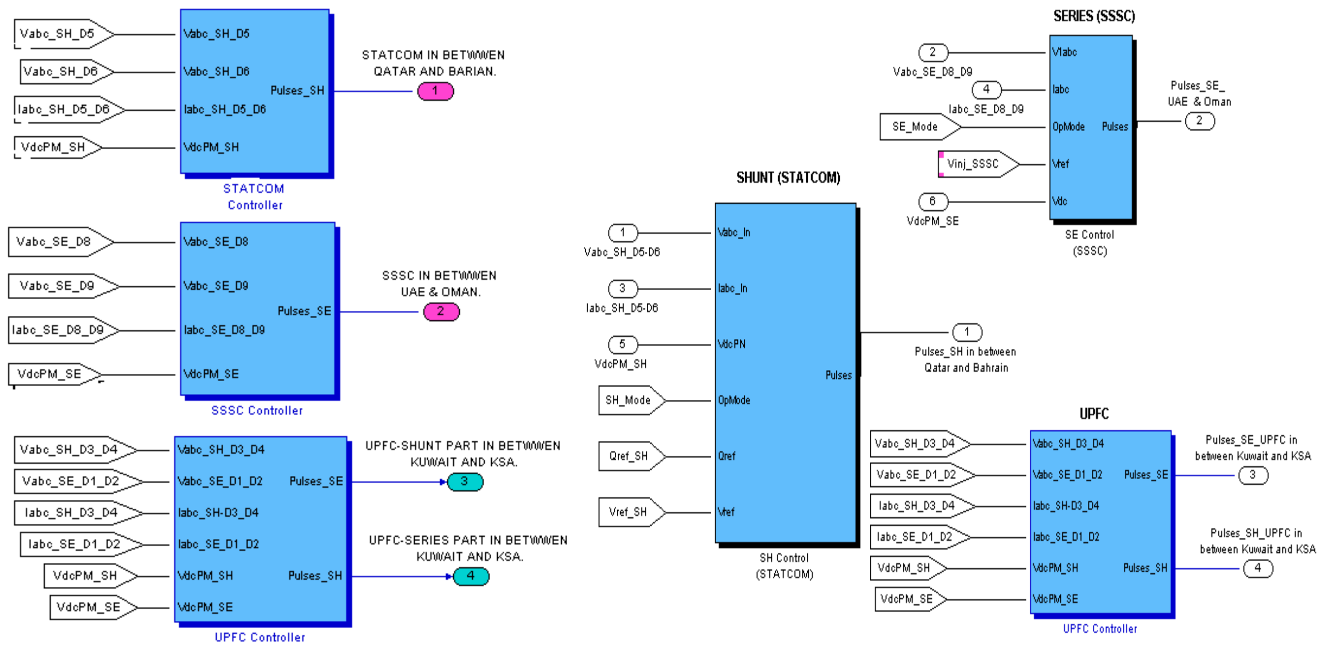

Figure 9-4: decentralized or independent control topology of the FACTS devices [Matlab]

9.6. FACTS devices external/master control (Centralized Control)

In Appendix 9.B there was introduced and investigated an external control loop that is communicating to all FACTS devices (STATCOM, SSSC & UPFC) in parallel operations through internal control loops of each device. The external control loop is controlling the devices based on the mean value of the deviation of all FACTS devices from different locations that are measured by the internal control loop in real-time operations. The primary function of this controller is to communicate an internal control loop to receive and send instructions based on defined operating and control boundaries of each device. The internal control loop is connected to each device and evaluating the deviations by comparing reference and measured value(s) of (line voltage, impedance and phase angle). All four internal control loops will deliver their control deviation inform of D5 &D6 (STATCOM), D8 & D9 (SSSC), UPFC (D1, D2-STATCOM and D3 & D4-SSSC) deviations operators as inputs to the external control loop as simulated and demonstrated in Figure 9-5 & 9-6.

After getting all four inputs the external control loop will calculate the mean value and generate control action to the final control elements parallel to all devices. Based on the input signals intensity, these devices will inject or absorb shared reactive power compensation 420Mvar minimum at +/-2% deviation, 840Mvar at +/-4% deviation medium and 1250Mvar at +/-6% deviation, maximum.

This shared reactive power will penetrate automatically within a fraction of second equally into the GCC power grid to overcome any operational contingencies. This is known as a centralized control system to control and monitor the device remotely at the Main Central Control Room (MCCR). All devices the internal controller is sending deviation refined signal inform of D5 &D6 (STATCOM), D8 & D9 (SSSC), UPFC (D1, D2-STATCOM and D3 & D4-SSSC) as demonstrated in control block Appendix 9.B in the master control loop. The external control system will be responsible for controlling the line voltage and power flow at different locations. This loop will also introduce two modes of operation, capacitive and inductive, based on the deviation to control each device remotely. The reference values of external control loop are demonstrated in Tables 9.5, 9.6, & 9.7.

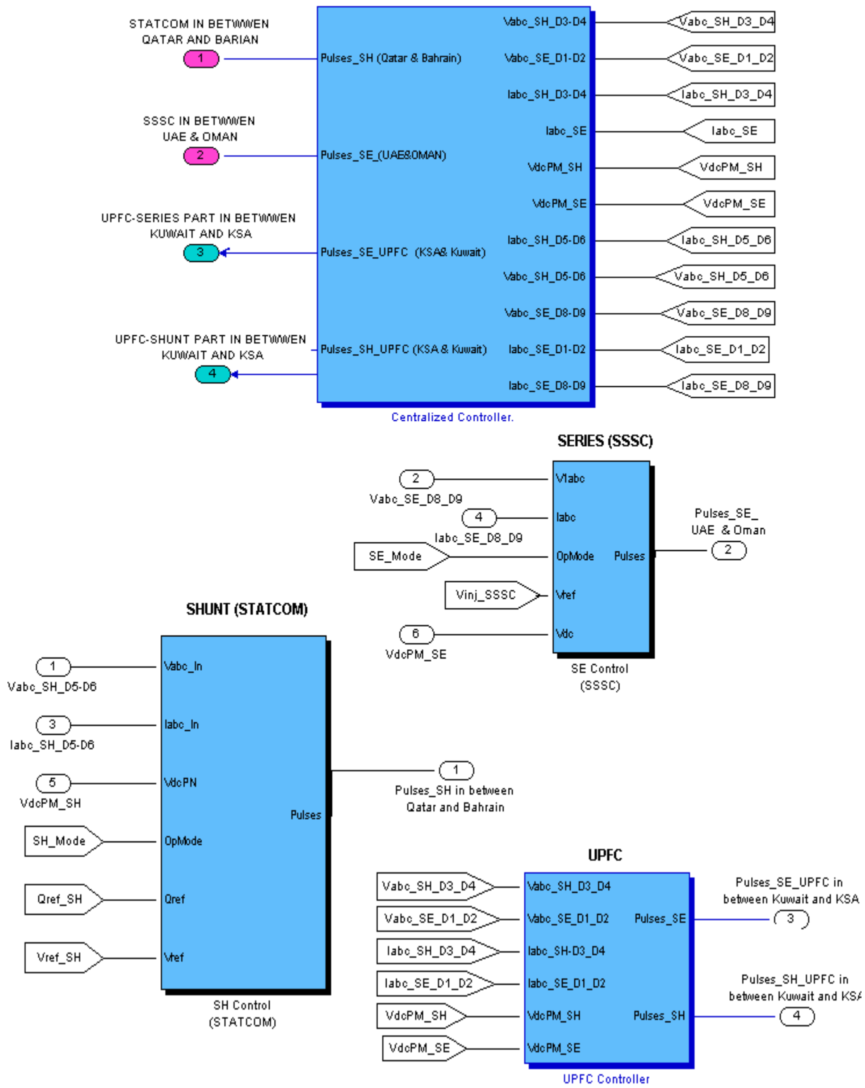

Figure 9-5: Centralized or integrated control topology [Matlab]

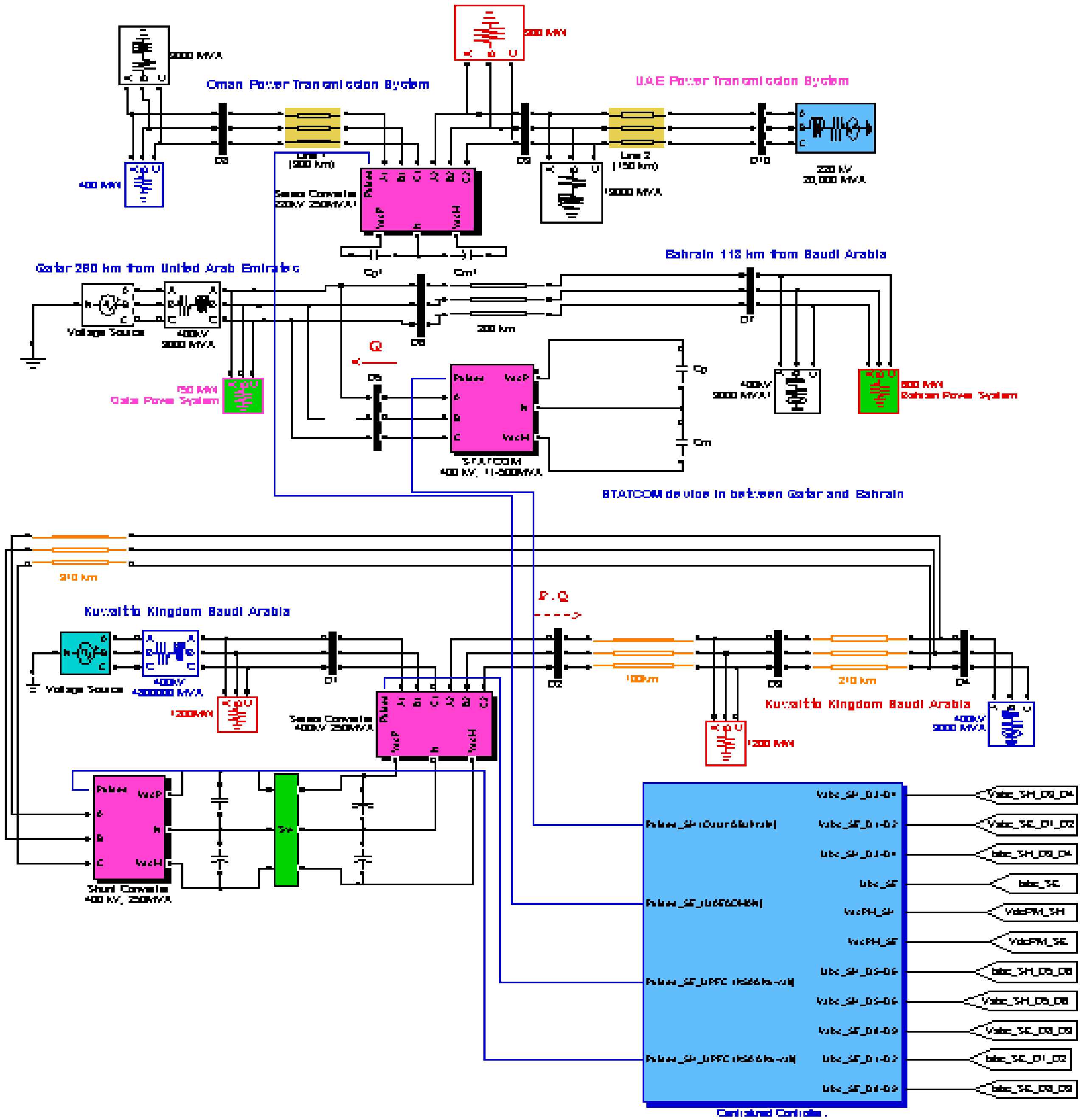

Figure 9-6: integrated STATCOM, SSSC and UPFC control devices on the GCC power grid [Matlab]

9.7. FACTS-FRAME case study:

9.7.1. STATCOM control device operations:

A 500-Mvar STATCOM regulates voltage on a three-bus 400kV long transmission system in the FACTS-FRAME. A 500-Mvar STATCOM implemented in between Qatar and Bahrain to regulate voltage on a three-bus 400kV in order to meet long transmission system operational requirements. Effectively, in normal operational conditions the STATCOM device adjusts the VSC (Voltage Source Converter) output to maintain its voltage in phase with the AC system voltage between Qatar and

Bahrain. The STATCOM device generates or absorbs the reactive power based on VSC (voltage source converter) output voltage. It is very important to understand that the amount of reactive based on converter output voltage magnitude and coupling transformer leakage reactance. The slight change in voltage angle will allow a small amount of reactive power to flow to the DC bus in order to charge or discharge capacitor bank. Appendices 1 & 2 illustrate 750 MW power exchanged by Qatar and 600 MW by Bahrain on the GCC Power grid [20], [21]. During the STATOCM operations the switches are synchronized with supply voltage from the GCC power grid (V). This assumed to be sinusoidal of frequency ω. Therefore the fundamental component, rms can be achieved as given below equation (9.1)

$$E_1 = \frac{\sqrt{2}}{\pi}\int_0^{\pi}\frac{V_{dc}}{2}\sin\theta d\theta = \frac{\sqrt{2}}{\pi}V_{dc} \qquad (9.1)$$

If $E_1 > V$ the STATCOM device draws a capacitive reactive current in between Bahrain and Qatar (D5 & D6) on the GCC power grid as indicated in Figure 9-4 and 9-6. Whereas it will be in inductive from of operations if $E_1 < V$.

9.7.2. SSSC control device operations:

A 250-Mvar SSSC regulates voltage on a three-bus 220-kV long transmission system in the FACTS-FRAME. A 250-Mvar SSSC controller adjusts converter output voltage in order to maintain 220kV AC system long transmission line between Oman and United Arab Emirates. In the steady operation of the SSSC control device, it maintains the Voltage source converter's fundamental components in-phase with the AC system between Oman and the UAE. In the first scenario if the converter output voltage is higher than the system voltage than the SSSC generates the reactive power to increase the system voltage against the reference value. If the AC system voltage is higher than the converter output voltage than the SSSC absorbs reactive power from the system to reduce the voltage. It has been identified and determined that the amount of reactive power depends on the VSC voltage magnitude and on the transformer leakage reactance. The voltage source converter components are controlled by varying the DC bus voltage. In order to charge or discharge the capacitor bank of the SSSC the VSC (Voltage source converter) is temporarily phase shifted to flow active power to the capacitor bank. This VSC voltage lag or lead produces a temporary flow of active power which results in an increase or a decrease of capacitor voltages. Appendices 1 & 2 illustrate 400MW power from or to Oman and 900MW from or to the United Arab Emirates on the GCC Power grid. As shown by the waveforms, the transmission line voltage and reactive current are well controlled by implementing the optimized control technique with a high degree of precision.

$$Re[V_s I^* *] = 0 \qquad (9.2)$$

$$V_s = V(\cos\gamma - j\sin\gamma)e^{j\varphi} \qquad (9.3)$$

Where: φ is the phase angle of the line current, γ is the angle by which V_S lag the current. Equation (9.2) indicates that V_S is in Quadrature with I current. If V_S lags I by 90 degree the SSSC operating mode is capacitive. As a result the magnitude of current is increased in the line which will lead to increase the power flow from UAE to Oman. Secondly, if V_S leads I by 90 degree the SSSC operating mode is inductive. As a result the magnitude of current is decreased in the line which will lead to decrease the power flow from UAE to Oman. (Refer for more detail in section 3.5)

9.7.3. UPFC control device operations:

The UPFC controller for the Kingdom of Saudi Arabia station was designed to maintain voltage and power flow control. This is also providing fast reactive shunt compensation with a total control range of +/- 500MVAR and controlling the power flow in the 400kV high capacity transmission line, forcing the transmitted power under contingency conditions up to 1200 MVA [60]. In order to increase the system reliability and provide flexibility for future system changes, the UPFC controller has to be configured in such a way to allow self-sufficient operations of the shunt converter as an independent STATCOM and a series converter as an independent Static Synchronous Compensator. These converters can be coupled to deliver either shunt only or series only compensation over a double control range [68].

9.7.4. STATCOM, SSSC and UPFC devices distributed control:

STATCOM, SSSC & UPFC devices consist of (+/-6 x3) controlled limits collectively to operate parallel by sharing reactive power compensation loads at different locations on the GCC power network. Each control device is configured by incorporating +/-2%, +/-4%, and +/-6% control and operating limits as a reference value for the final control elements to adjust the converter gating pattern logic. In the control schematic there are six control blocks that are configured from left to right as stated in Appendix 9.D. the first block measured the line voltage and the second block measured the line current of the power system network as stated below. Based on these measured values the deviation is calculated against the reference values of each block. These deviations are sent to final control block to generate required action to send parallel signal to all three devices to reduce or eliminate deviations. If the deviation is +/-2 then all three devices will activate in parallel to inject or absorb +/-420Mvar minimum reactive power in the transmission system at their locations. At +/-4% all three devices will activate in parallel to inject or absorb +/- 840Mvar medium reactive power in the transmission system at their locations on the GCC power grid. At +/-6% all three devices will activate in parallel to inject or absorb +/-840Mvar reactive maximum reactive power in the transmission system at their locations on the GCC power grid. Below, the simulation results indicate the effectiveness of integrated FACTS devices operations and stringent control to address time-based power transmission systems contingencies.

9.8. Observations:

9.8.1. Integrated STATCOM operations in the FACTS-FRAME:

Figure 9-7 is demonstrating the network response without STATCOM operations. Figure 9-8 indicates the network behavior with STATCOM, and in the first trace there is variation of Vs and Vp voltage at coupling transformer, but significant change observed in Ip primary side current in following pattern (1.0 pu to -1.0pu), (0.5pu to -0.5pu), and (1.5pu to -1.5pu). In the second trace variation in the Vdc voltage observed, it spiked from 0.007 to 0.2 second dropped at 22kV for 0.55 seconds and rose up to 21kV and stayed there to continue the rest of the operations. In the third trace the variation in Q_ measure and Q_ ref was observed. The Q_ measure shows variation from -0.35pu to -1.0pu and again oscillated after 0.5 seconds as reactive power demand increased from -0.35pu to 0.85pu and stayed there to continue rest of operations. In the last trace, variation in Vref against V_ measure observed, the V_ measure shows spike 1.01pu within 0.1 second and dropped at 0.99pu in 0.5 second and stayed there to continue rest of operations. The STATCOM model demonstrates very strong impact on GCC power grid in order to achieve following benefits. Figure 9.3 and Figure 9.4 indicate the power flow improvement profile at receiving before and after the STATCOM (switched off and on).

- 750 MW power exchanged at Doha South Substation Qatar
- 600MW power exchanged at Al-Jasra substation Bahrain
- Improved power flow in between Qatar and Bahrain
- Meeting industrial and domestic load requirements at different atmospheric conditions without any constraint.

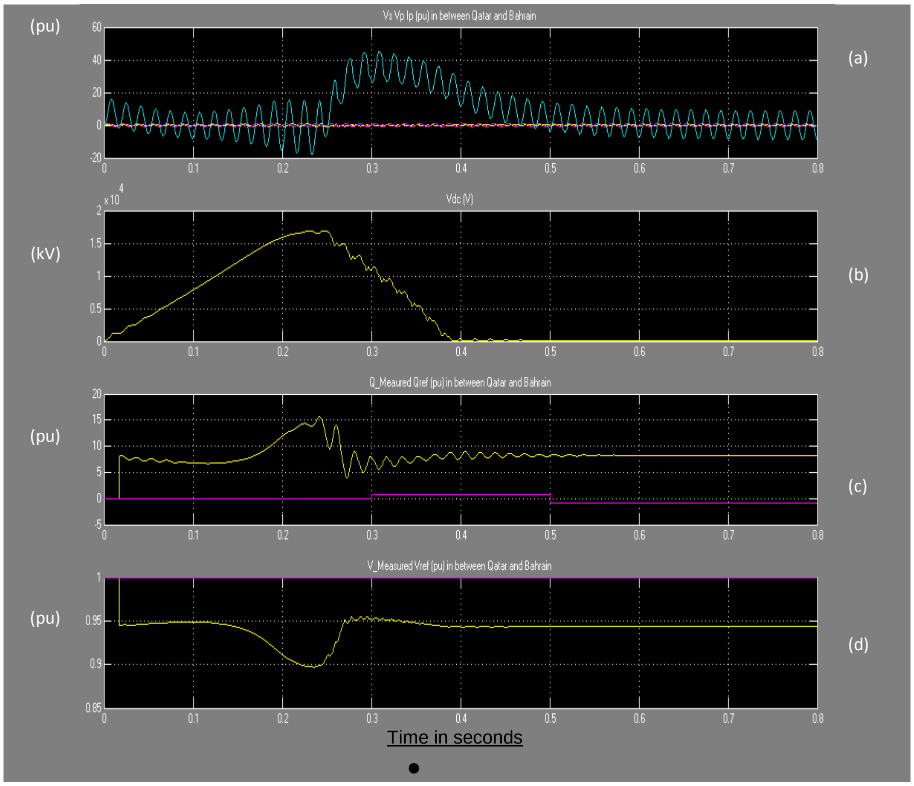

Figure 9-7: Network operational trends without integrated STATCOM (a) primary and secondary voltage and current (b) measured value of DC voltage (c) measured and reference reactive power (d) measured and reference voltage

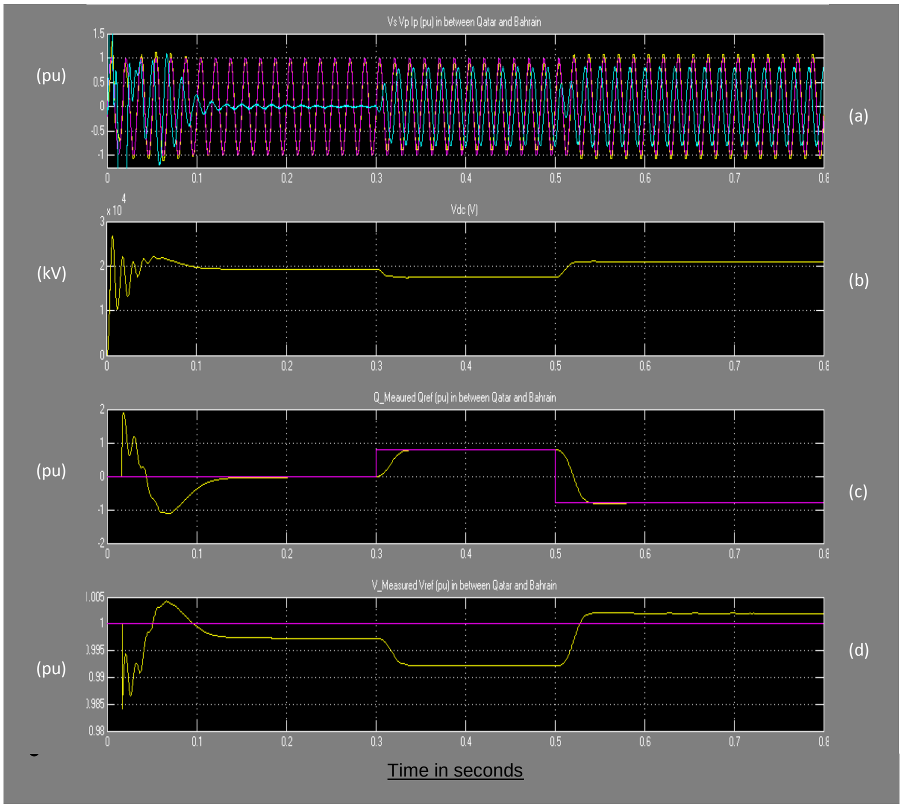

Figure 9-8: Network operational trends with integrated STATCOM (a) primary and secondary voltage and current (b) measured value of DC voltage (c) measured and reference reactive power (d) measured and reference voltage

9.8.2. Integrated SSSC operations in the FACTS-FRAME

Figure 9-9 indicates the network response without SSSC operations between Oman and the United Arab Emirates. Figure 9-10 is showing the SSSC operations results in integrated FACTS-FRAME. I In the first trace there is variation of V_{inj} voltage injected in series, the magnitude was -0.02pu to 0.02pu for 0.35 seconds and gradually increased up to -0.09pu to 0.09pu, and then stayed at -0.08 to 0.08 for continue rest of operations. In the second trace variation in Iabc observed, there is small slight dent (1.0pu-1.0pu) for 0.1 to 0.35 second and a rise up (1.05pu to -1.05pu) for 0.35 to 0.8 and it then stayed there for rest of the operations. In the third trace variation of Mag _Vinj and Vref was observed, the Vref changed from 0pu to 0.85pu for 0.3 to 0.44 second and stayed there for the rest of the operations. In the fourth trace Vdc voltage was observed, it spiked up to 18kV for 0.03 to 0.43 second and stayed there to continue th erest of the operations. In the last two traces variation of reactive (Mvar) and active power (MW) at each line was observed. The SSSC model demonstrates very strong impact in between Oman and UAE in the GCC power grid in order to achieve following benefits. Figure 9-5 and 9-6 indicate the voltage profile at receiving end before and after the SSSC (switched off and on)

- 400 MW power exchanged at Al-wasset Substation Oman
- 900MW power exchanged at Al-Ouhah substation UAE.
- Improved load flow in between Oman and UAE
- Meeting industrial and domestic load requirements at different atmospheric conditions without any constraint.

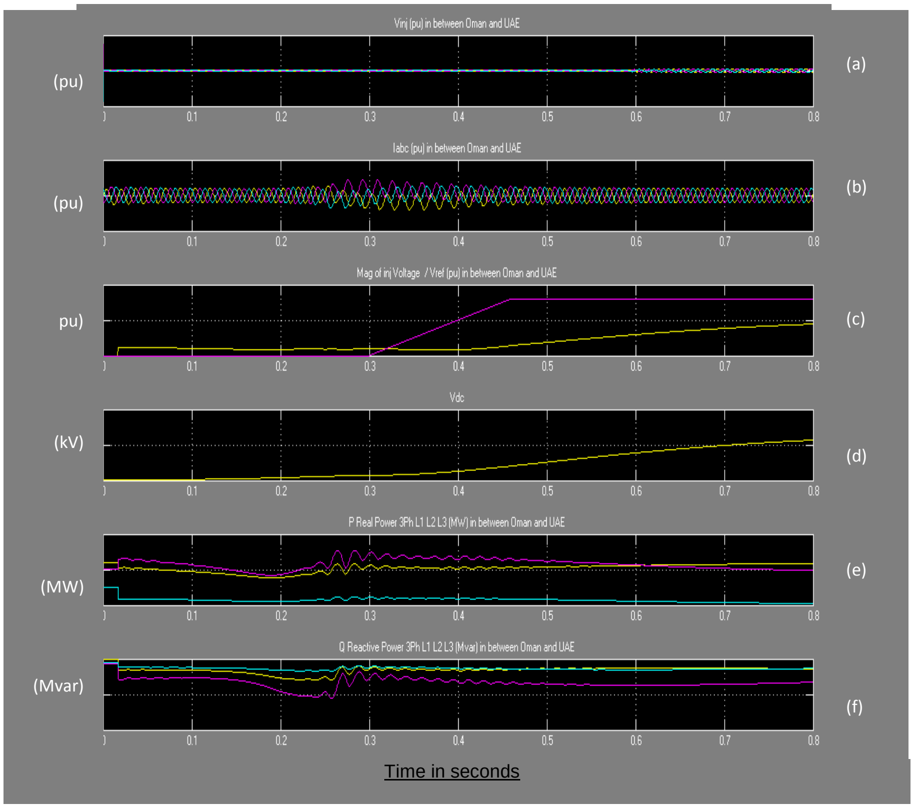

Figure9-9: Network operational trends without integrated SSSC (a) injected voltage in series (b) three phases measured and reference current (c) measured and reference value of injected voltage (d) measured value of DC voltage (e) three phases real power (f) three phases reactive power

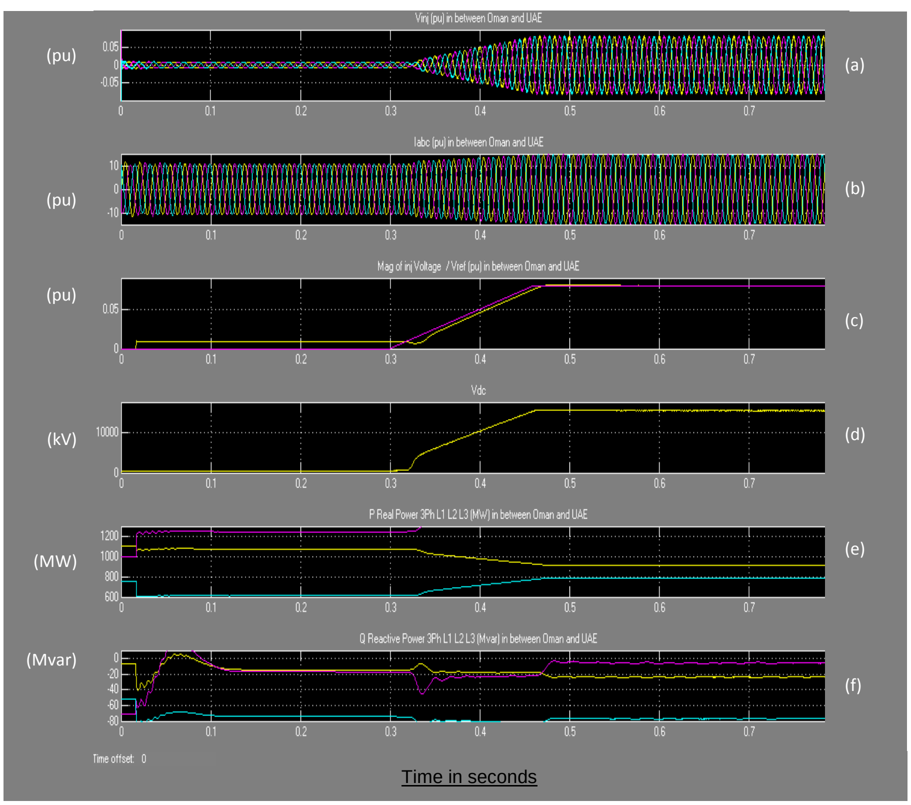

Figure 9-10: Network operational trends with integrated SSSC (a) injected voltage in series (b) three phases measured and reference current (c) measured and reference value of injected voltage (d) measured value of DC voltage (e) three phases real power (f) three phases reactive power

9.8.3. Integrated UPFC operations in the FACTS-FRAME

Figure 9-11 indicates the network response without UPFC operations between Kuwait and KSA. Figure 9-12 demonstrates the network response with UPFC operations in the FACTS-FRAME. In the first trace there is variation of P against Pref observed, the Pref was 5pu for 0.25 second and then increased to 12pu and stayed there for rest of the operations.

Similarly, the P varied for 0.25 to 0.55 seconds and spiked up to 12pu to match with Pref and then stayed there to continue the rest of the operation. In the second trace there is variation of Q against Qref observed, the Qref was -0.2pu for 0.5 second and then increased up to 2pu and stayed there for the rest of the operations. Similarly, the Q varied for 0.001 to 0.15 seconds and spiked up to 2pu after 0.7 seconds to match with Qref and then stayed there to continue the rest of the operation. In the last two traces variation of reactive (Mvar) and active power (MW) at each line was observed.

The SSSC model demonstrates very strong impact in between Oman and UAE in the GCC power grid in order to achieve following benefits. Figure 9-7 and 9-8 indicate the voltage profile at receiving end before and after the SSSC (switched off and on)

- 1200 MW power exchanged at Al-Fadhili Substation KSA on the GCC power grid
- 1200MW power exchanged at Al-Zour substation UAE on the GCC power grid
- Improved load flow in between KSA and Kuwait
- Meeting industrial and domestic load requirements at different atmospheric conditions without any constraint.

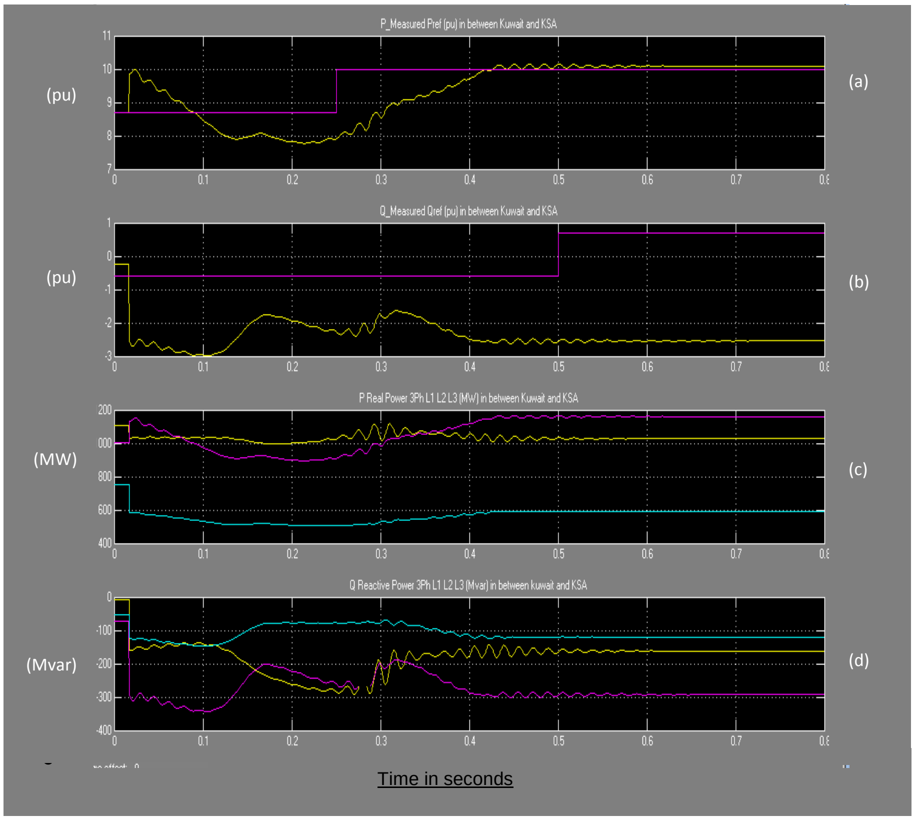

Figure 9-11: Network operational trends without integrated UPFC (a) measured and reference power (b) measured and reference reactive power (d) three phases real power (f) three phases reactive power

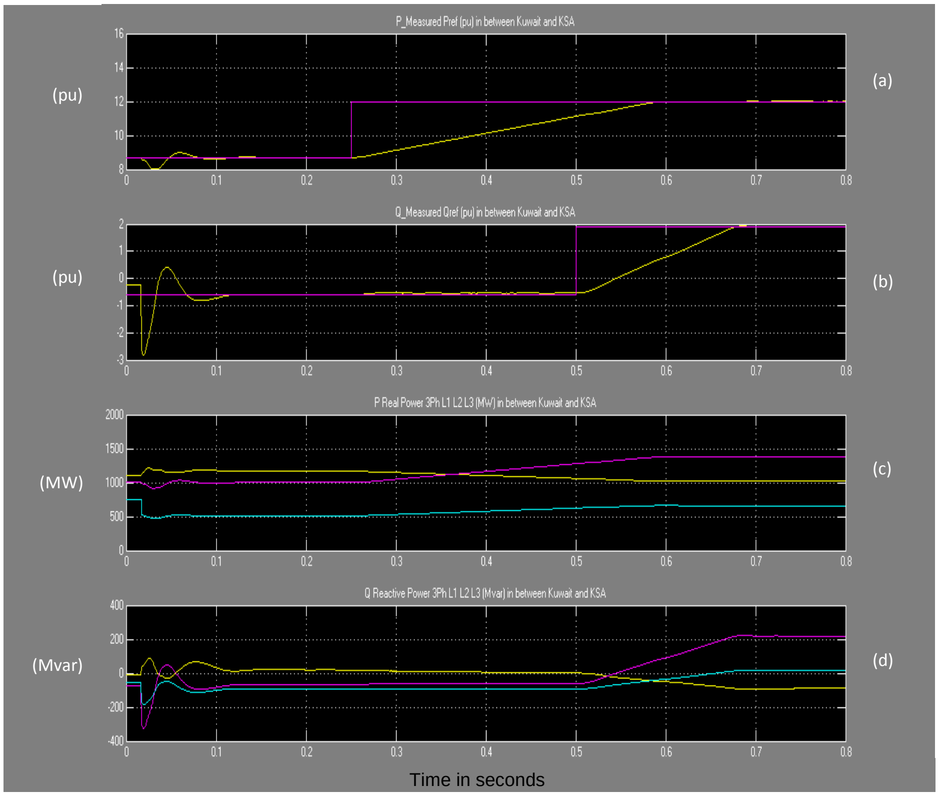

Figure 9-12: Network operational trends with integrated UPFC (a) measured and reference power

(b) measured and reference reactive power (d) three phases real power (f) three phases reactive power

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9.9. FACTS controllers integration

In order to establish the FACTS-FRAME baseline, it is very important to build its control and operational capacity and capability. Table 9.1 indicates the classified data into two categories e.g. Static and Dynamic Data to analyze the intensity and suitability of this data. This data is incorporated as reference operating and control ranges as input values into the control blocks of the internal and external control loops.

Table 9.2 shows country ID, power ID voltage ID against the defined power and voltage values e.g. V5 and V9 indicates the 220kV voltage at C5 and C9 (Oman and United Arab Emirates) the rest of the GCC power system is operating at 400kV and 50Hz. These IDs and values are plugged-in control block 1 & 3 as reference values of the internal and external (master) control loops as shown in appendices 9.A & 9.B. These control blocks will determine the deviation against the measured values for final action for internal or external control loops. The measured values are fetched from different locations on the GCC power grid at different operating conditions. Table 9.3 shows the power change IDs, voltage change IDs, country IDs and stations IDs e.g. VC1 (-/+) 0- 0.55% to VC9 (-/+) 4.46-5.02%. On a similar pattern: PC1 (-/+) 2% to PC9 (-/+) 18%. These are the controller reference values which are plugged into block 5 from left to right internal and external control loops of an appendix 9.A and 9.B, based on the deviation the controller will act. Table 9.3 also illustrates the small step size of variation to determine operational viability of each device during the compensation mode of operations. Table 9.4 indicates the STATCOM, SSSC & UPFC parallel operations in capacitive and inductive mode of operations. It also shows the corresponding PI control value of each control action. These values are plugged in control blocks external (master) and internal (slave) control loops of appendix.9.A & 9.B to enforce required compensation by considering STATCOM and SSSC & UPFC controllers action from minimum to maximum at a small step size to the AC system on the GCC power grid.

9.9.1. FACTS controllers implementation

Based on Table 9.3, if the VC1 to VC9 are greater than the converter voltage, than the STATCOM, SSSC & UPFC will absorb reactive power from the AC power system parallel by employing three controls and operating limits. Hence the converter current is perpendicular to the converter voltage if the VC1 to VC9 are lesser/greater than the converter voltage, than the STATCOM, SSSC & UPFC will generate/ absorb reactive power to the AC power system. Based on new research, there are three limits that have developed each FACTS' devices (minimum, medium and maximum). By implementing this approach, there are numerous benefits that can be witnessed. In the first control scenario all three of the control devices have a large margin to generate or absorb reactive power compensation without overloading the system. Secondly, the control system will generate a quicker response at a minimum compensation factor based on the deviation. All three FACTS devices will share the compensation load by injecting or absorbing 420Mvar reactive power and this will enhance power system stability and reliability considerably [79], [80]. Based on these input PI controller configured to maintain these three limits more precisely as demonstrated in Chapter no.9 and calculated PI controllers values are depicted in appendices 7 to 13 of the same chapter.

1) If the deviation is small (-/+2%) than all three FACTS devices will be on capacitive or inductive mode of operations at six control patterns at different locations.
2) If the deviation is medium (-/+4%) than all three FACTS devices will be on capacitive or inductive mode of operations at six control patterns at different locations.
3) If the deviation is bigger (-/+6) than all three FACTS devices will be on capacitive or inductive mode of operations at six control patterns at different control locations.

These devices will activate automatically against the defined voltage and power transfer deviation demonstrated at S1/C1, S7/C7 and S6/C6 (substation-ID/country-ID) in Table 9.3 and 9.4.

9.9.2. FACTS-FRAME system architecture input data

These layers are communicating to each other as per defined operating and control boundaries as stated in Table 9.1 to 9.7.

Table 9.1 demonstrates FACTS devices input data functionalities. This contains two types of data one is static and other dynamic. Firstly, the static data comprises of each country IDs, substation IDs, operational zones, and FACTS devices operating status (on and off). Mainly, the static data covered various operational properties on the GCC power grid operational devices. Secondly the dynamic data contains control deviation from a different location as well as three control patterns of FACTS devices to adjust the converter gating response.

TABLE 9.1: FACTS DEVICES INPUT DATA FUNCTIONALITY

Table Name	Data-Type	Purpose	Consequence If Data Not Present
GCC	STATIC	Contains a list (ID numbers, Name, zone and station) on the GCC. Each Country is assigned to a particular function	Reference Data - Mandatory
FACTS_STATCOM	DYNAMIC	Contains shunt controller, current injection in phase with the line voltage into system at the point of connection only supply or consumes reactive power	strong impact on voltage control medium impact on system stability and load flow control
FACTS_SSSC	DYNAMIC	Contains series controller, voltage injection into with the line current quadture of the AC system at the point of connection, AC voltage magnitude can be varied by changing modulation ratio	Strong impact to increase system performance by reducing the line impedance
FACTS_UPFC	DYNAMIC	Contains series voltage and shunt current compensation controllers	strong impact to enhance power transmission performance, voltage, load flow and stability

Table 9.2 demonstrates operating parameters voltage, power and line impedance area wise. It also shows each country's power exchange as well as line voltage at nine substations within six countries. This table also indicates the voltage level at nine locations station-wise between the six GCC countries. Table 9.2 indicates the STATIC data on the GCC power grid operations, which is used to identify different operational aspects, e.g. line voltage-ID, power-ID, country-ID and substation-ID as well as defined zones. These IDs are configured during the modeling and simulation process.

TABLE 9.2: OPERATING VOLTAGE AND POWER OF THE EACH GCC COUNTRY

STATIONID	STATIONNAME	COUNTRYID	COUNTRY NAME	VOLTAGEID	VOLTAGEkV	POWERID	MW
S1	Alzour	C1	Kuwait	V1	400	P1	1200
S2	Alfidhli	C2	Saudi Arabia	V2	400	P2	1200
S3	Salwa	C3	Saudi Arabia	V3	400	P3	750
S4	Ghunan	C4	Saudi Arabia	V4	400	P4	600
S5	Al-wasset	C5	Oman	V5	220	P5	400
S6	Al-Sil'a	C6	UAE	V6	400	P6	900
S7	Doha South	C7	Qatar	V7	400	P7	750
S8	Jasra	C8	Bahrian	V8	400	P8	600
S9	Al-Fuhah	C9	Oman	V9	220	P9	400

Table 9.3 demonstrates power deviation (+/-2, +/-4, and +/-6%) and controllable compensation at nine locations station wise. This table also indicates the geographical position of each station and its corresponding country on the GCC power network. Table 9.3 indicates the nine substations and their IDs location-wise and their corresponding power change in % as well as voltage variation IDs at each substation. Based on these IDs, it is very important to thoroughly understand and examine any operational and control constraints at a specific location e.g. station (S1, S2…S9) or area country-wise (C1, C2, C3…C9) on the GCC power grid. This is very important to configure these points more carefully in the model as defined in Table 9.3 to witness the accuracy in real operations during the modeling and simulation.

TABLE 9.3: CORRESPONDING POWER AND VOLTAGE CHANGE (+/-)

STATIONID	STATIONNAME	POWER CHANGE ID	POWER CHANGE %	VOLTAGE CHANGE ID	VOLTAGE CHANGE%
S1	Alzour	PC1	+/- 2%	VC1	0 - 0.55%
S2	Alfidhli	PC2	+/-4%	VC2	0.55% - 1.11%
S3	Salwa	PC3	+/-6%	VC3	1.11 %- 1.67%
S4	Ghunan	PC4	+/-8%	VC4	1.67 %- 2.23%
S5	Al-wasset	PC5	+/-10%	VC5	2.23 %- 2.79%
S6	Al-Sil'a	PC6	+/-12%	VC6	2.79 %- 3.35%
S7	Doha South	PC7	+/-14%	VC7	3.35 %- 3.91%
S8	Jasra	PC8	+/-16%	VC8	3.91 %- 4.46%
S9	Al-Fuhah	PC9	+/-18%	VC9	4.46 %- 5.02%

Table 9.4 demonstrates the STATCOM, SSSC and UPFC three control limits and corresponding PI control values. These PI control values are incorporated to adjust STATCOM, SSSC & UPFC converters gating responses into three control limits to generate/absorb reactive power compensation ((+/-2, +/-4, and +/-6%) at different location on the GCC power grid. Table 9.4 indicates the individual and joint control operations of all three FACTS devices. In this table nine control patterns of three FACTS devices are demonstrated in chronological order. Each control pattern indicates its defined control and operating limits. These control limits have three operating and control ranges likewise +/-2, +/-4, and +/-6%. In the first control range all the three devices will generate a minimum response in parallel operation, on the second control range medium and on the third control range these devices will be on full capacitive or inductive mode of parallel operations. Effectively, these three devices will share the load and provide reactive power compensation +/-420Mvar at minimum deviation and +/-840Mvar at medium deviation and 1250Mvar at maximum deviation. These distributed control limits provide an excellent flexible in-parallel operation of these devices without any constraint or overloading of the system.

TABLE 9.4: COMBINATIONS OF THREE FACTS DEVICES (+/-)

DEVICE ID	DEVICE NAME	COUNTRYID STATIONID	CAPACTIVIE CONTROL ID	P (POR)	I (INT)	REFERENCE VOLTAGE(kV)	MEASURED VOLTAGE (kV)	ERROR IN %
ST	STATCOM	S1/C1	CC1/LC1	0.32	0.6	440	437.58	+/-2%
ST	STATCOM	S1/C1	CC11/LC11	0.36	0.8	440	435.12	+/-4%
ST	STATCOM	S1/C1	CC111/LC111	0.38	0.9	440	432.66	+/-6%
SS	SSSC	S7/C7	CC2/LC2	0.32	0.6	440	427.74	+/-2%
SS	SSSC	S7/C7	CC22/LC22	0.36	0.8	440	425.28	+/-4%
SS	SSSC	S7/C7	CC222/LC222	0.38	0.9	440	422.82	+/-6%
UP	UPFC	S6/C6	CC3/LC2	0.32	0.6	440	417.90	+/-2%
UP	UPFC	S6/C6	CC33/LC22	0.36	0.8	440	415.44	+/-4%
UP	UPFC	S6/C6	CC333/LC333	0.38	0.9	440	412.98	+/-6%

Table 9.5 indicates the line voltage, power and frequency at different locations on the GCC power grid. This contains six countries (Qatar, Bahrain, Oman, Kuwait, KSA and United Arab Emirates). Table 9.5 demonstrates operating parameters that are measured at different locations on the GCC power grid. These parameters are very important to configure and simulate steady or dynamic control models by integrating FACTS devices. This table indicates that the GCC power grid divided into six subsystems based on the GCC power system's operational requirements. Firstly, the Qatar power system is connected to the GCC 400kV, 50Hz power grid at the Doha south substation to share 750MW. Secondly, the Bahrain power system is connected to the GCC 400kV, 50Hz power grid at Al-ghunan substation to share 600MW. Thirdly, the UAE power system is connected to the GCC 400kV 50Hz power grid at Salwa substation to share 900MW. Fourthly, the Oman power system is connected to the GCC 220kV 50Hz power grid at Al-Sila substation in the UAE to share 400MW. Fifthly, the KSA

power system is connected through the DC link to synchronize 60Hz KSA power system to the GCC 400kV, 50 Hz power grid to share 1200MW.

TABLE 9.5: POWER VOLTAGES AND FREQUENCE

Countries	Power Exchange, Voltage & Frequency
To the Qatar or from Qatar to main transmission line	750MW, 400kV, 50Hz
To the Bahrain or from Bahrain to main transmission line	600MW, 400kV, 50Hz
To the UAE or from the UAE to the main transmission line	900MW, 400kV, 50Hz
To the Oman or from the Oman to the main transmission line	400MW, 220kV, 50Hz
Power exchanged from Kuwait to main transmission line	1200MW, 400kV, 50Hz
Power exchanged from Kingdom Saudi Arabia to main transmission line	1200MW, 400kV, 60Hz DC link to convert 60Hz to 50 Hz frequency

Table 9.6 indicates the existing reactive power (fixed reactor and capacitor) in place and their distance location-wise on the GCC power grid. Table 9.6 demonstrates the current reactive power requirements on the GCC power grid, which is being met by using conventional devices (reactors and capacitors banks). The GCC power grid reactive power management indicates four critical areas at different locations on the GCC power grid based on transmission lines distance to each other. Based on various studies, the first location is identified to provide +/- 500Mvar reactive power compensation in between the Al-Fadhi and Al-Ghunan substation in KSA. The second location is identified to provide +/- 850Mvar reactive power compensation in between the Al-Ghunan and Salawa substation in the KSA. The third location is identified and determined to provide +/-500Mvar between the Slawa to Doha South substations. The fourth location is determined to provide 250Mvar in between the Al-Sila and Al-Fuhah substations. These analyses indicate that the total reactive power demand is 2100Mar on the GCC power grid by using conventional control devices.

TABLE 9.6: EXISTING REACTIVE POWER AND DISTANCE

Existing Power System	Reactive Power	Distance
Reactive Power Demand at Al-Ghunan substation KSA	500MVAR	Al Fadhili substation (KSA) to Al-Ghunan Substation (KSA) =114 Km
Reactive Power Demand at Al Jasra substation Bahrain	850MVAR	Al-Ghunan Substation (KSA) to Slawa Substation (Qatar) = 288Km
Reactive Power demand at Al-Salwa Substation	500MVAR	Slawa Substation (Qatar) to Doha South Substation = 97Km
Reactive Power demand at Doha South Substation	250MVAR	

A table 9.7 indicates each device location Iq regulators (Kp and Ki) and all three controller droops (0.033p.u./100MVAR). This table also indicates all three control devices are parallel in operations and each device distributed control pattern (minimum, medium, maximum) to generate/absorb reactive power for compensation.

Table 9.7 indicates the STATCOM, SSSC, and UPFC controllers' devices locations based on the wideband Dephi technique demonstrated in Chapters 5, 6, and 7. Firstly, location is identified and determined to implement STATCOM TO provide +/- 500Mvar dynamic reactive power compensation between Qatar (Doha South) and Bahrain (Al-ghunan-KSA substations intertie connection to the Bahrain). The STATCOM control block indicates the Iq regulator control response (kp =12dB; Ki=35dB). The second control block of the STATCOM indicates the P & I values to inject and absorb reactive power compensation based on three control boundaries as discussed in section 9.9. The second location is identified and assessed to implement SSSC to provide +/- 250Mvar in between the UAE (Al-Sila) and Oman (Al-Fuhah Substation). The SSSC control block indicates the Iq regulator control response (kp =10dB; Ki=33dB). The second control block of the SSSC indicates the P & I values to inject and absorb reactive power compensation based on three control boundaries as discussed in section 9.9.

TABLE 9.7: MULTIVARIABLE CONTROLLER'S CONFIGURATION:

Locations: STATCOM (Qatar and Bahrain) SSSC (Oman and UAE) UPFC : Kuwait and KSA	Iq regular: Kp 12dB; Ki: 35dB Iq regular: Kp 10dB; Ki: 32dB Iq regulator: Kp: 10 dB; Ki 34 dB	CC1/CL1, CC2/LC2, CC3/CL3 = Minimum compensation capacitive or inductive (VC voltage change from +/-2%)
Rated STATCOM: +/- 500 MVAR SSSC: +/- 250 MVAR UPFC: +/- 500MVAR	Ref V: 1.0 pu (220kV)	CC11/CL11, CC22/LC22, CC33/CL33 = medium compensation capacitive or inductive (VC voltage change from +/- 4%)
P (proportional): 0.32 , 0.42 and 0.52 I (integral) 0.6, 0.8, 0.9, 1.1 D (derivative): none	Droop: 0.033pu/100MVA; Kp:14dB; Ki: 3500dB	CC111/CL111, CC222/LC222, CC333/CL333 = full compensation capacitive or inductive (VC voltage change from +/-6%)

The third location is identified and examined to implement UPFC to provide +/- 500Mvar reactive power compensation between Kuwait (Al-zour) and KSA (Al-Fadhili substation). The UPFC control block indicates the Iq regulator control response (kp =10dB; Ki=34dB). The second control block of the UPFC indicates the P & I values to inject and absorb reactive power compensation based on three control boundaries as discussed in section 9.9. These models have the capacity and capability to run independently and jointly without any constrains. Herein various dependencies are created and applied successfully by integrating different interfaces. Each device will activate or deactivate its operations as per a customized control set of parameters as described in Table 9.7.

9.10. <u>Results and discussion:</u>

The prime aim of the FACTS-FRAME technique is to integrate all FACTS devices parallel in operations to generate/absorb reactive power compensation at different locations. The simulation results indicate that the FACTS-FRAME technique is providing large operational and control flexibility on the GCC power grid without any constraints. FACTS devices' integration provides numerous benefits. If there is a small (+/-2%) deviation on power transfer or voltage quality all three devices will generate/absorb time-based reactive power in parallel to eliminate the deviation. On the same control pattern if the deviation is medium (+/-4%) on power flow and voltage quality, all three devices will activate and generate/absorb reactive power compensation respectively. Lastly, if the deviation is large (+/-6%) on the power flow and voltage quality, all three devices will activate and generate/absorb reactive power compensation accordingly.

By this technique one of the devices can be isolated for maintenance purpose for the long- or short-term basis or backup without disturbing network operations at different locations. This will also increase the uptime of the various equipments without any genuine or spurious trips. The results show that FACTS-FRAME has a versatile capability by integrating all FACTS devices to provide reliable, continuous control of the transmission line current, provide dynamic control of power flow, reduce fault current, damps SSR oscillation, improve the voltage profile, power angle and stability margin on the GCC power grid. It also exhibits a positive impact on neighboring countries' power system operations on the GCC power grid.

9.11. Summary:

In this chapter, a multi-variable controller was developed which will be able to communicate and control all FACTS devices (STATCOM, SSSC, and UPFC) that are in operation at any one time. An optimization technique was developed to identify and determine the composite location of the FACTS devices and their operating parameters, which are providing reactive power compensation as appropriate to enhance over-all network performance and reducing the network losses. The results indicate massive improvement if all devices are parallel in operation at different locations on the GCC power grid. In order to share an appropriate power (real or reactive), different combinations of FACTS devices and their corresponding PI controllers have been developed and implemented to obtain very promising results. Based on study STATCOM, SSSC and UPFC models are customized to serve the purpose. Furthermore as a drawback standpoint of this study, the power exchange ought to be monitored and examined on a critical basis to take preventive measures for any possible network violation, which may lead to the GCC blackout.

CHAPTER 10

Significance of this Research Work

10.1 PI Controller Configuration Parameters Selection Process & Significance:

The STATCOM, SSSC and UPFC control devices' parallel operational responses are customized by using P & I configuration parameters. These parameters are identified and implemented to share the control responses into three operating and control limits to adjust minimum, medium and maximum reactive power compensation in both capacitive and inductive mode of operations. A first set of PI control model's detailed calculations are performed and a mathematical model developed and synthesized by incorporating a new set of PI configuration values as demonstrated in Appendix 5.A 6.A & 7.A. Firstly, to control the 400kV power transmission line voltage of the AC power system between the Qatar and Bahrain as well as KSA and Kuwait, secondly 220kV power transmission line voltage of the AC power system between the Oman and United Arab Emirates on the GCC power network.

On a time-domain simulation results are very encouraging and validating the PI controller robustness. Based on these results and effective integration, a multiple portal of the controller was developed and synthesized which is leading to run all three devices in parallel or independently to overcome any type of power transmission line contingences at different location(s) on the GCC power network as simulated and demonstrated in Appendix 9.D

These models are developed based on worst case scenarios to investigate most optimum PI control parameters to manipulate and adjust reactive power compensation as per defined three control limits, but in the real world these models will demonstrate different operating and control boundaries based on voltage and power deviation on the sending and receiving ends of the AC power system. In the first case, if the deviation is large then the controller needs a big step size to inject or absorb reactive power to minimize the deviation and stabilize the control loop. In the second case, if the deviation is small then the controller will take a small step size to inject and absorb reactive power in order to minimize the deviation on the AC power system. By dividing and distributing the PI controller operating and control parameters to integrate into three small limits (operating ranges) which will provide tangible and ultimate control on reactive power compensation with small step size without any constraints. This will also lead to making the controller response faster. However, the results indicate that this approach has a great potential to enhance controller dynamic performance at a minimum cost and it may stabilize the control loop within 10-15 iteration. This is an instrumental concept to address a wide range of power system stability issues and control integration without any additional control support on the GCC power network.

10.2 Internal and External Controls Significance:

In order to control the STATCOM, SSSC and UPFC devices individually and jointly (integrated) a well-controlled- five-layers mesh distributed control system was developed to manipulate and adjust the reactive power compensation based on line voltage, impedance, phase angle and power flow deviation at different locations on the GCC countries, this is also called the FACTS-FRAME as shown in Figure 9-1 and 9-2. In the first layer of control, all existing parameters on the GCC power grid are incorporated independently into internal control of the FACTS-FRAME. In the second layer of control, the STATCOM, SSSC and UPFC devices control and operating parameters are incorporated. In the third layer of control, the GCC countries defined operational limitation and required reactive power compensations are incorporated as shown in Tables 9.1 to 9.7. In the fourth layer of the control, STATCOM, SSSC and UPFC devices integration and independency of the control topologies are incorporated. In the fifth layer a distributed control system is introduced with two control patterns decentralized & centralized as demonstrated in Appendices 9.A (internal control) and 9.B (external control). Firstly, the decentralized control is implemented to control the STATCOM, SSSC & UPFC devices operations independently and locally based on their operating and control parameters deviation (voltage, impedance and power flow) at their locations. Chapters 5, 6 and 7 reveal the individual FACTS devices simulation results that are very much encouraging and promising.

After successful implementation, the decentralized control system will provide independent FACTS devices operations but at limited control and operating margins. These devices will offer well-controlled load flow, power stability by series compensation and voltage quality by shunt compensation at different locations on the GCC power grid. In fact, this type of control topology did not offer a control flexibility to share the operational load and to carry out routine maintenance from time to time. For routine maintenance of any FACTS device, it is very important to isolate partially or fully the certain power system facilities for a certain period of time if there is no backup.

Secondly, the centralized control system offers an excellent control flexibility and robustness. The centralized control is implemented to control the STATCOM, SSSC & UPFC devices operations collectively and remotely, based on their operating parameters deviation (voltage, impedance, angle, power flow). Chapter 9 demonstrates the integrated FACTS devices operational results which are very encouraging and promising. Through a centralized control system numerous benefits can be witnessed after its successful application. This system will provide parallel FACTS devices at a wide operating margin. The centralized control system will make available well-controlled load flow, power stability by series compensation and voltage quality by shunt compensation at different locations on the GCC power grid. Furthermore, this type of control topology has great potential to share the operational load and to perform routine maintenance from time to time without any system downtime and process ambiguity by isolating any device from the power system.

10.3 Operational and Maintenance Control Significance:

These both centralized and decentralized control topologies have a great potential to run these devices in a multiple mode of operations without any constraints. By implementing centralized control topology, numerous benefits can be witnessed during this operation. Firstly, in summer case, there is high power demand from the domestic and industrial consumers on the GCC countries. In order to meet high power demands all three devices will operate parallel to meet wide-range of operational requirements at different locations on the GCC power grid in real-time operations. The centralized controller has a capability to link or delink the relevant device(s) (STATCOM, SSSC & UPFC) to inject or absorb reactive power as well as to increase or reduce the real power transfer to meet the AC power system requirements. This is also known as extensive flexible power system operations.

The second capability of this controller is to share the reactive power load in between two or three devices as per the AC power system needs. In winter case, there is low power demand from the domestic and industrial consumers on the GCC countries. The simulation results indicate that at off-peak power demand two FACTS devices parallel operations can provide adequate reactive power compensation to the AC power transmission system on the GCC power grid and the other device can be on standby mode as a spinning reserve or can be isolated for maintenance purpose. In this operational scenario the most important and critical part is to select the most optimum combination of these devices e.g. STATCOM-SSSC or UPFC-STATCOM or UPFC-SSSC. During this combination one device will be on standby mode all the time and it will resume its operations only in an emergency case. After long run of any two devices combination one of them can be isolated for schedule or preventive maintenance by replacing standby device. This type of maintenance operational strategy will provide maximum uptime of the power system without any type of downtime by implementing predictive and proactive corrective maintenance strategic programmes. In order to implement these programmes effectively, the SAP and MAXIMA industrial applications have been implemented in many companies. First type of maintenance strategy is a predictive maintenance. This is also called the Time-Based-Maintenance (TBM) which is costly but more effective. Second type of maintenance strategy is a proactive corrective maintenance. This is also called the Condition-Based-Maintenance “run to failure” (RTF) which is cheaper and effective. This type of operational strategy also provides monetary benefit to the company as well as wide range of operational flexibility.

10.4 FACTS Devices Selection Process’s Significance

Based on comprehensive feedback received from the highly skilled personnel from industry and academia, a strong portal is developed for the STATCOM, SSSC & UPFC. These inputs are integrated by using *Wideband Delphi* technique in order to investigate, generate and allocate near optimal values of significant and submission criteria(s) as established in Tables 5.1, 5.2 and 5.3 for the STATCOM, Tables 6.1, 6.2, 6.3 for the SSSC and 7.1, 7.2, 7.3 for the UPFC. As the results are demonstrated in the tables which indicate the strengths of each FACTS device based on 12 areas criteria significance. The STATCOM is a first candidate to be installed in between the Qatar and Bahrain on the GCC power grid. The STATCOM has a great potential to diminish the effect of grid disturbance and susceptible on load near the load center. The SSSC is a second candidate to be installed in between the UAE and Oman on the GCC power grid. The SSSC has a great potential to be installed near the critical substation in order to mitigate low voltage during active power swing as well as to prevent excessive under or overvoltage circumstances in the event of if any major power line or generation lost on the GCC power grid. The UPFC is a third candidate to be installed in between the KSA and Oman on the GCC power grid. The SSSC has a great potential to be installed near the supply point of major industrial and other types of commercial loads in order to support temporary under or overvoltage conditions. These devices will also act as compensator in order to improve voltage quality on the GCC power grid whenever there is disturbance.

10.5 STATCOM, SSSC & UPFC Controllers Integration Significance:

These devices consist of 18 controlled limits collectively to operate in parallel by sharing reactive power compensation loads at different locations on the GCC power network. Each device comprises 6 operating and control; limits three positive (+2, +4, +6) and three negative (-2, -4, -6). Which split each limit's corresponding capacitive and inductive compensation factor? These limits are operating on a small step size to inject or absorb reactive power based on each control limit's corresponding PI control parameters. These controllers control and operate boundaries and their corresponding PI values are configured by using the *Cooper Douglas* control technique as discussed in Chapter 9. The corresponding PI control values are simulated and are against each control limit to (+/-) to accelerate or de-accelerate the STATCOM, SSSC & UPFC operations in order to meet required reactive power compensation at defined locations on the GCC power grid.

Furthermore, these control limits are plugged into internal control loop's calculation blocks as described in Appendix 9.A. These blocks have been configured by incorporating reference values against the measured variables of voltage, current and firing angle. After getting the measured variable from different locations on the GCC power grid, these control blocks are calculating the operational and control deviation by using reference values against the measured variables. Based on the identified deviation the control blocks will determine the required reactive power compensation at each operational point and generate a signal (+/-). If the control and operational deviation is small +/-

2% than the FACTS controller will adjust minimum its converter gating response with its minimum corresponding PI control values in order to meet minimum reactive power compensation. If the deviation is medium +/-4% than the FACTS controller will adjust its medium gating response with its medium corresponding PI values to meet medium compensation to the power system network. Similarly, if the deviation is large +/- 6% than the FACTS controller will adjust maximum its converter gating response with it maximum corresponding PI control value in order to meet maximum reactive power compensation on the GCC network.

CHAPTER 11

Conclusions

This thesis presents the development of five inter-related works (geographical position of each country, location of each device, each device selection process, integrated communication interface of STATCOM, SSSC & UPFC, and control pattern of each FACTS device). A framework for implementation of the aforementioned FACTS devices on the GCC power grid has been investigated in order to achieve the following benefits:

- Increased power transfer capability and capacity in the GCC power grid.
- Improved GCC power grid operational reliability
- Improved GCC power grid controllability
- Enhanced angular and voltage stability

In this research work long transmission lines basic principals are discussed, operating parameters and compensation level and how these could be obtained by putting its operational and security criticalities into consideration is also discussed. Hereby, simple shunt and series compensation techniques are adopted to develop STATCOM, SSSC and UPFC models for implementation in order to provide appropriate shunt and series compensation in the GCC power grid as applicable.

The STATCOM control device connection between the Qatar and Bahrain: **s**hunt compensation and its operating parameters viabilities and criticalities are investigated. By using a STATCOM control device both capacitive and inductive modes of operations are demonstrated by putting its control and operational criticalities into consideration. Simulation results indicate the effectiveness of the STATCOM control device between Qatar and Bahrain. A detailed STATCOM model is designed, configured and implemented between Qatar and Bahrain on the GCC power grid. In this study, two new techniques are introduced and their effectiveness is demonstrated. Firstly, the STATCOM device selection process was introduced by implementing the *Wideband Delphi methodology* and another technique is used to share STATCOM control device operations into three control limits; this is known as a *Douglas Cooper PID* controller's optimization. The primary aim of the STATCOM device selection and implementation purpose is to enhance voltage quality between Qatar and Bahrain and it has a medium-positive impact on power system stability that has been obtained by implementing a new control technique. In this technique three control limits are investigated and synthesized to share the STATCOM operational response in order to provide reactive power compensation in shunt based on the power transmission network operating parameters deviation (+/-). If the deviation is small, from (+/-) 2%, the STATCOM device will activate in order to inject/absorb minimum reactive power compensation. Secondly, if the deviation is medium (+/-) 4%, the STATCOM device will activate to inject/absorb medium reactive power compensation and the maximum compensation will activate if the deviation is above (+/-) 6%.

The SSSC control device connection between Oman and the United Arab Emirates: series compensation and its operating parameters viabilities and criticalities are investigated. By using SSSC both capacitive and inductive modes of operations are demonstrated by putting its control and operational criticalities into consideration. Simulation results indicate the effectiveness of the SSSC control device between Oman and the United Arab Emirates. A detailed SSSC model is designed, configured and implemented between Oman and the United Arab Emirates on the GCC power grid. In this case study, two new techniques are introduced and their effectiveness is demonstrated. Firstly, the SSSC device selection process introduced by implementing the *Wideband Delphi methodology* and another technique is used to share SSSC control device operations into three control limits; this is known as a *Douglas Cooper PID* controller's optimization. The primary aim of the SSSC device selection and implementation purpose is to enhance power system stability between Oman and the United Arab Emirates and it has a small impact on voltage quality and power flow which has been obtained by implementing the aforementioned new control technique.

In this technique, three control limits are investigated and synthesized to share the SSSC operational response to provide reactive power compensation in series based on power transmission network operating parameters deviation (+/-). If the deviation is small (+/-) 2%, the SSSC device will activate to inject/absorb minimum reactive power compensation. Secondly, if the deviation is medium (+/-) 4%, the SSSC device will activate to inject/absorb medium reactive power compensation and the maximum compensation will activate if the deviation is (+/-) 6%.

The UPFC control device connection between the KSA and Kuwait: unified power flow controller (Series and shunt) compensation and its operating parameters viabilities and criticalities are investigated. By using UPFC both capacitive and inductive modes of operations are demonstrated by putting its control and operational criticalities into consideration. Simulation results indicate the effectiveness of the UPFC control device between the KSA and Kuwait. A detailed UPFC model is designed, configured and implemented between the KSA and Kuwait on the GCC power grid. In this study, two new techniques are introduced and their effectiveness is demonstrated. Firstly, the SSSC device selection process introduced by implementing *Wideband Delphi* methodology and another technique is used to share UPFC control device operations into three control limits. The primary aim of the UPFC device selection and implementation is to enhance power system stability, voltage quality and load flow between the KSA and Kuwait that has been obtained by implementing the aforementioned new control technique.

In this technique three control limits are investigated and synthesized to share the UPFC operational response to provide reactive power compensation based on power transmission network operating parameters deviation (+/-). If the deviation is small (+/-) 2%, the UPFC device will activate to inject/absorb minimum reactive power compensation. Secondly, if the deviation is (+/-) 4%, the UPFC device will activate to inject/absorb medium reactive power compensation and the maximum compensation will activate if the deviation is (+/-) 6%.

The PI, PID controller tuning and configuration: the developed work is an unconventional control loop optimization technique, which has been adopted to fine-tune, optimize and share STATCOM, SSSC and UPFC controls by using PID, PD, PI controller constant and variable configuration parameters to adjust these devices operations at different locations on the GCC power grid during any undesired operating conditions. The primary aim is to identify, determine and address vulnerable areas and operating boundaries of different control loops of target FACTS devices that are in operation at a particular time to sustain and enhance the performance of the power system. These devices will directly or indirectly impact on network performance (improving voltage quality, power flow and power stability) by providing time based adequate reactive power compensation whenever required.

Three different control and operating boundaries are identified and determined for each device to inject or absorb minimum, medium or maximum reactive power on the GCC power grid. To validate this technique, six control models are developed and simulated by incorporating 'P' and 'I' configuration parameters. Simulation results indicate the effectiveness of PI control parameters to "divide and rule" the control operations of each device. Each control boundary is carrying its corresponding P & I values to adjust each device's response accordingly.

The FACTS-FRAME architecture: FACTS-FRAME is developed and configured by integrating various layers of control and operations in the GCC power grid. The first layer describes the geographical positions of the each GCC country. The second layer describes the geographical location of each FACTS device(s) and their static and dynamic operational data requirements for application. The third layer describes the selection process of required FACTS device based on its capability and capacity to overcome power transmission system's contingences on the GCC power grid. The fourth layer describes the communication interface to integrate STATCOM, SSSC and UPFC to each other. The fifth layer describes the control pattern of each FACTS device. These patterns are configured based on each device's time based capability and capacity to inject and absorb reactive power (capacitive/inductive) mode of operations of the AC power system. A new technique is introduced and it demonstrates reactive power compensation in three modes of operations (minimum, medium and maximum) based on control deviation. To maintain these three control boundaries the PI controller's response is configured and integrated based on deviations. If deviation is (+/-) 2% the controller will inject or absorb minimum reactive power for (+/-) 4% medium reactive power and for (+/-) 6% maximum reactive power.

During this study, it has been also identified that the KSA power facilities are operating at 60Hz and the rest of the countries are operating at 50Hz. Therefore back-to-back DC link is an instrumental approach to develop an asynchroniz communication link between the two frequencies; the KSA and rest of the GCC countries. The major power generation facilities are installed in the KSA and Kuwait. The study also indicates that the HVDC system is a very viable solution to deliver bulk power through a long transmission line from the KSA to the rest of the GCC countries. After successful implementation of DC-link at the al-Fidlhali substation the KSA is sharing 1200MW power on the GCC power grid**.** This solution is also very economical and providing well-controlled power transmission flow from the KSA to rest of the GCC countries**.**

Based on the aforementioned outcomes, a multi-variable controller has been developed and implemented to communicate and provide distributed control to all FACTS devices (STATCOM, SSSC, and UPFC) that are in operation parallel at time by implementing a centralized control system as discussed earlier in a sequence. During centralized control all three devices' response will be adjusted parallel based on power transmission network operating parameters deviation (+/-) 2%, (+/-) 4%, and (+/-) 6% to inject/absorb reactive power compensation. As a conclusion, after successful implementation of the centralized control system the following benefits can be witnessed convincingly on the GCC power grid.

1. Reduction in installation and operational cost on the GCC power grid
2. Maximum uptime of the power system network on the GCC power grid
3. One device can be isolated during off-peak/peak for maintenance or overhauling purposes
4. One device can be on a standby or backup mode of operations for emergency purposes
5. More flexible operations without overloading any area, region or device
6. More reliable by sharing rapid reactive power compensation as per network system needs.
7. Providing adequate and wide-range stability margins on the GCC power grid.
8. Providing one window operations at minimum manpower
9. Shared and more flexible protection control topologies can be established
10. Well-controlled unified power flow on the GCC power network without any constraints.

During decentralized control all three devices' converter gating response will be adjusted independently based on their defined location power transmission network operating parameters deviation (+/-) 2%, (+/-) 4%, and (+/-) 6% to inject/absorb reactive power compensation. As a conclusion the decentralized control system may acquire the following outcomes.

1. High installation and operational cost
2. Potential of the power network violation area or region-wise which may lead to the downtime of particular equipment, area or region.
3. No alternate for maintenance or overhauling of the device that may lead to downtime of particular equipment, area or region.
4. No flexible operations sometimes overloading individual areas, regions or devices
5. Providing an adequate stability margin on their individual operations-based power transmission network operating parameters deviation.

Future work on the GCC power grid:

1. Further investigation is required to identify and determine a potential network violation incurred due to FACTS devices implementation that may lead to GCC blackout.
2. As a drawback of this study, the power exchange ought to be monitored and examined on a critical basis to take preventative measures for any possible network violation in order to prevent any possible blackout of the whole GCC countries.
3. When all HVDC/FACTS devices are in operations through centralized control (Protection control topology functionality and constraint on the GCC power grid to be determined).
4. When all three HVDC/FACTS devices are in operations independently through decentralized control (Protection control topology functionality and constraint on the GCC power grid to be determined.

CHAPTER 12

Appendices

Appendix: 4. A For explanation refer sections/subsection: 4.7, 4.7.1, 4.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	**Proportional**	**0.32**				
2	**Integral**	**0.6**				
3						
4	**SP**	**400 kV**				
5				**ABSOLUTE**		
6	Iteration	**PV**	**ERROR**	**ERROR**	**OUTPUT**	**INTEGRAL**
7					0	0
8					0	0
9	1	0	400	400	128	76.8
10	2	0	400	400	204.8	153.6
11	3	0	400	400	281.6	230.4
1	4	128	272	272	317.44	282.624
2	5	204.8	195.2	195.2	345.088	320.1024
13	6	281.6	118.4	118.4	357.9904	342.8352
14	7	317.44	82.56	82.56	369.2544	358.6867
15	8	345.088	54.912	54.912	376.2586	369.2298
16	9	357.9904	42.0096	42.0096	382.6729	377.2957
17	10	369.2544	30.7456	30.7456	387.1343	383.1988
18	11	376.2586	23.74144	23.74144	390.7961	387.7572
19	12	382.6729	17.327104	17.327104	393.3019	391.084
20	13	387.1343	12.8657408	12.8657408	395.201	393.5542
21	14	390.7961	9.2039168	9.2039168	396.4995	395.3214
22	15	393.3019	6.69814784	6.69814784	397.4648	396.6074
23	16	395.201	4.798980096	4.798980096	398.1431	397.5288
24	17	396.4995	3.500541542	3.500541542	398.649	398.2009
25	18	397.4648	2.535235584	2.535235584	399.0122	398.6877
26	19	398.1431	1.856924877	1.856924877	399.2819	399.0442
27	20	398.649	1.351021036	1.351021036	399.4765	399.3036
28	21	399.0122	0.987814966	0.987814966	399.6197	399.4933
29	22	399.2819	0.71810916	0.71810916	399.7231	399.6311
30	23	399.4765	0.523468813	0.523468813	399.7986	399.7316
31	24	399.6197	0.380298717	0.380298717	399.8533	399.8047
32	25	399.7231	0.276944101	0.276944101	399.8933	399.8578
33	26	399.7986	0.201352053	0.201352053	399.9223	399.8965
34	27	399.8533	0.146660472	0.146660472	399.9434	399.9247
35	28	399.8933	0.106716595	0.106716595	399.9588	399.9451
36	29	399.9223	0.077732783	0.077732783	399.97	399.9601
37	30	399.9434	0.056574495	0.056574495	399.9782	399.9709
38	31	399.9588	0.041197725	0.041197725	399.9841	399.9788
39	32	399.97	0.029982959	0.029982959	399.9884	399.9846
40	33	399.9782	0.021828916	0.021828916	399.9916	399.9888
41	34	399.9841	0.01588718	0.01588718	399.9939	399.9918
42	35	399.9884	0.011565942	0.011565942	399.9955	399.9941
43	36	399.9916	0.008418507	0.008418507	399.9968	399.9957
44	37	399.9939	0.006128711	0.006128711	399.9976	399.9969
45	38	399.9955	0.004461169	0.004461169	399.9983	399.9977
46	39	399.9968	0.003247687	0.003247687	399.9987	399.9983
47	40	399.9976	0.002364068	0.002364068	399.9991	399.9988

48	41	399.9983	0.001720969	0.001720969	399.9993	399.9991
49	42	399.9987	0.001252739	0.001252739	399.9995	399.9994
50	43	399.9991	0.000911941	0.000911941	399.9996	399.9995
51	44	399.9993	0.000663832	0.000663832	399.9997	399.9997
52	45	399.9995	0.000483239	0.000483239	399.9998	399.9998
53	46	399.9996	0.000351769	0.000351769	399.9999	399.9998
54	47	399.9997	0.000256071	0.000256071	399.9999	399.9999
55	48	399.9998	0.000186405	0.000186405	399.9999	399.9999
56	49	399.9999	0.000135694	0.000135694	399.9999	399.9999
57	50	399.9999	9.87772E-05	9.87772E-05	400	399.9999

Appendix: 4.B For explanation refer sections/subsection: 4.7, 4.7.1, 4.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	Proportional	0.36				
2	Integral	0.8				
3						
4	SP	400kV				
5				ABSOLUTE		
6	Iteration	PV	ERROR	ERROR	OUTPUT	INTEGRAL
7					0	0
8					0	0
9	1	0	400	400	144	115.2
10	2	0	400	400	259.2	230.4
11	3	0	400	400	374.4	345.6
1	4	144	256	256	437.76	419.328
2	5	259.2	140.8	140.8	470.016	459.8784
13	6	374.4	25.6	25.6	469.0944	467.2512
14	7	437.76	-37.76	37.76	453.6576	456.3763
15	8	470.016	-70.016	70.016	431.1706	436.2117
16	9	469.0944	-69.0944	69.0944	411.3377	416.3125
17	10	453.6576	-53.6576	53.6576	396.9958	400.8591
18	11	431.1706	-31.17056	31.17056	389.6377	391.882
19	12	411.3377	-11.33773	11.33773	387.8004	388.6167
20	13	396.9958	3.004211	3.004211	389.6983	389.482
21	14	389.6377	10.36227	10.36227	393.2124	392.4663
22	15	387.8004	12.19957	12.19957	396.8581	395.9798
23	16	389.6983	10.30173	10.30173	399.6884	398.9467
24	17	393.2124	6.787623	6.787623	401.3902	400.9015
25	18	396.8581	3.141861	3.141861	402.0326	401.8064
26	19	399.6884	0.311606	0.311606	401.9185	401.8961
27	20	401.3902	-1.390214	1.390214	401.3956	401.4957
28	21	402.0326	-2.032575	2.032575	400.764	400.9103
29	22	401.9185	-1.918539	1.918539	400.2197	400.3578
30	23	401.3956	-1.395626	1.395626	399.8554	399.9559
31	24	400.764	-0.763995	0.763995	399.6808	399.7358
32	25	400.2197	-0.219666	0.219666	399.6568	399.6726
33	26	399.8554	0.144624	0.144624	399.7246	399.7142
34	27	399.6808	0.319178	0.319178	399.8291	399.8061
35	28	399.6568	0.34325	0.34325	399.9297	399.905
36	29	399.7246	0.275369	0.275369	400.0041	399.9843
37	30	399.8291	0.170878	0.170878	400.0458	400.0335
38	31	399.9297	0.070289	0.070289	400.0588	400.0538
39	32	400.0041	-0.00413	0.00413	400.0523	400.0526

40	33	400.0458	-0.045819	0.045819	400.0361	400.0394
41	34	400.0588	-0.05882	0.05882	400.0182	400.0224
42	35	400.0523	-0.052273	0.052273	400.0036	400.0074
43	36	400.0361	-0.036075	0.036075	399.9944	399.997
44	37	400.0182	-0.018199	0.018199	399.9904	399.9917
45	38	400.0036	-0.003616	0.003616	399.9904	399.9907
46	39	399.9944	0.005608	0.005608	399.9927	399.9923
47	40	399.9904	0.009562	0.009562	399.9958	399.9951
48	41	399.9904	0.009553	0.009553	399.9985	399.9978
49	42	399.9927	0.007274	0.007274	400.0004	399.9999
50	43	399.9958	0.004236	0.004236	400.0014	400.0011
51	44	399.9985	0.001485	0.001485	400.0017	400.0016
52	45	400.0004	-0.000446	0.000446	400.0014	400.0014
53	46	400.0014	-0.001447	0.001447	400.0009	400.001
54	47	400.0017	-0.001677	0.001677	400.0004	400.0005
55	48	400.0014	-0.001409	0.001409	400	400.0001
56	49	400.0009	-0.00092	0.00092	399.9998	399.9999
57	50	400.0004	-0.000421	0.000421	399.9997	399.9997

Appendix: 4.C For explanation refer sections/subsection: 4.7, 4.7.1, 4.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	Proportional	0.38				
2	Integral	**0.9**				
3						
4	SP	**400kV**				
5				**ABSOLUTE**		
6	Iteration	**PV**	**ERROR**	**ERROR**	**OUTPUT**	**INTEGRAL**
7					**0**	**0**
8					0	0
9	1	0	400	400	152	136.8
10	2	0	400	400	288.8	273.6
11	3	0	400	400	425.6	410.4
1	4	152	248	248	504.64	495.216
2	5	288.8	111.2	111.2	537.472	533.2464
13	6	425.6	-25.6	25.6	523.5184	524.4912
14	7	504.64	-104.64	104.64	484.728	488.7043
15	8	537.472	-137.472	137.472	436.465	441.6889
16	9	523.5184	-123.5184	123.5184	394.7519	399.4456
17	10	484.728	-84.728	84.728	367.249	370.4686
18	11	436.465	-36.46496	36.46496	356.6119	357.9976
19	12	394.7519	5.248096	5.248096	359.9919	359.7925
20	13	367.249	32.75104	32.75104	372.2379	370.9933
21	14	356.6119	43.38806	43.38806	387.4808	385.832
22	15	359.9919	40.00811	40.00811	401.0351	399.5148
23	16	372.2379	27.76215	27.76215	410.0644	409.0095
24	17	387.4808	12.51922	12.51922	413.7668	413.291
25	18	401.0351	-1.035113	1.035113	412.8977	412.937
26	19	410.0644	-10.06442	10.06442	409.1125	409.495
27	20	413.7668	-13.76676	13.76676	404.2636	404.7868
28	21	412.8977	-12.89769	12.89769	399.8856	400.3757
29	22	409.1125	-9.112545	9.112545	396.913	397.2593
30	23	404.2636	-4.263623	4.263623	395.6391	395.8011
31	24	399.8856	0.114363	0.114363	395.8446	395.8402

32	25	396.913	3.087017	3.087017	397.0133	396.896
33	26	395.6391	4.360917	4.360917	398.5531	398.3874
34	27	395.8446	4.155442	4.155442	399.9665	399.8086
35	28	397.0133	2.986721	2.986721	400.9435	400.83
36	29	398.5531	1.446879	1.446879	401.3798	401.3249
37	30	399.9665	0.033526	0.033526	401.3376	401.3363
38	31	400.9435	-0.943521	0.943521	400.9778	401.0136
39	32	401.3798	-1.37984	1.37984	400.4893	400.5417
40	33	401.3376	-1.337598	1.337598	400.0334	400.0843
41	34	400.9778	-0.977786	0.977786	399.7127	399.7499
42	35	400.4893	-0.489301	0.489301	399.5639	399.5825
43	36	400.0334	-0.033448	0.033448	399.5698	399.5711
44	37	399.7127	0.287283	0.287283	399.6803	399.6693
45	38	399.5639	0.436061	0.436061	399.835	399.8185
46	39	399.5698	0.430178	0.430178	399.9819	399.9656
47	40	399.6803	0.319739	0.319739	400.0871	400.0749
48	41	399.835	0.164953	0.164953	400.1376	400.1314
49	42	399.9819	0.018056	0.018056	400.1382	400.1375
50	43	400.0871	-0.087099	0.087099	400.1044	400.1077
51	44	400.1376	-0.137631	0.137631	400.0555	400.0607
52	45	400.1382	-0.138223	0.138223	400.0082	400.0134
53	46	400.1044	-0.10444	0.10444	399.9737	399.9777
54	47	400.0555	-0.05545	0.05545	399.9566	399.9587
55	48	400.0082	-0.008155	0.008155	399.9556	399.9559
56	49	399.9737	0.02628	0.02628	399.9659	399.9649
57	50	399.9566	0.043382	0.043382	399.9814	399.9798

Appendix: 9.D For explanation refer sections/subsection: 9.7, 9.7.2, 9.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	Proportional	0.32				
2	Integral	**0.6**				
3						
4	SP	**220kV**				
5				**ABSOLUTE**		
6	Iteration	**PV**	**ERROR**	**ERROR**	**OUTPUT**	**INTEGRAL**
7					0	0
8					0	0
9	1	0	220	220	70.4	42.24
10	2	0	220	220	112.64	84.48
11	3	0	220	220	154.88	126.72
1	4	70.4	149.6	149.6	174.592	155.4432
2	5	112.64	107.36	107.36	189.7984	176.0563
13	6	154.88	65.12	65.12	196.8947	188.5594
14	7	174.592	45.408	45.408	203.0899	197.2777
15	8	189.7984	30.2016	30.2016	206.9422	203.0764
16	9	196.8947	23.10528	23.10528	210.4701	207.5126
17	10	203.0899	16.91008	16.91008	212.9238	210.7594
18	11	206.9422	13.057792	13.057792	214.9378	213.2664
19	12	210.4701	9.5299072	9.5299072	216.316	215.0962
20	13	212.9238	7.07615744	7.07615744	217.3606	216.4548
21	14	214.9378	5.06215424	5.06215424	218.0747	217.4267
22	15	216.316	3.683981312	3.683981312	218.6056	218.1341
23	16	217.3606	2.639439053	2.639439053	218.9787	218.6408

24	17	218.0747	1.925297848	1.925297848	219.2569	219.0105
25	18	218.6056	1.394379571	1.394379571	219.4567	219.2782
26	19	218.9787	1.021308682	1.021308682	219.605	219.4743
27	20	219.2569	0.74306157	0.74306157	219.7121	219.617
28	21	219.4567	0.543298231	0.543298231	219.7908	219.7213
29	22	219.605	0.394960038	0.394960038	219.8477	219.7971
30	23	219.7121	0.287907847	0.287907847	219.8893	219.8524
31	24	219.7908	0.209164294	0.209164294	219.9193	219.8926
32	25	219.8477	0.152319255	0.152319255	219.9413	219.9218
33	26	219.8893	0.110743629	0.110743629	219.9572	219.9431
34	27	219.9193	0.08066326	0.08066326	219.9689	219.9586
35	28	219.9413	0.058694127	0.058694127	219.9773	219.9698
36	29	219.9572	0.042753031	0.042753031	219.9835	219.978
37	30	219.9689	0.031115972	0.031115972	219.988	219.984
38	31	219.9773	0.022658749	0.022658749	219.9913	219.9884
39	32	219.9835	0.016490627	0.016490627	219.9936	219.9915
40	33	219.988	0.012005904	0.012005904	219.9954	219.9938
41	34	219.9913	0.008737949	0.008737949	219.9966	219.9955
42	35	219.9936	0.006361268	0.006361268	219.9975	219.9967
43	36	219.9954	0.004630179	0.004630179	219.9982	219.9976
44	37	219.9966	0.003370791	0.003370791	219.9987	219.9983
45	38	219.9975	0.002453643	0.002453643	219.9991	219.9987
46	39	219.9982	0.001786228	0.001786228	219.9993	219.9991
47	40	219.9987	0.001300238	0.001300238	219.9995	219.9993
48	41	219.9991	0.000946533	0.000946533	219.9996	219.9995
49	42	219.9993	0.000689007	0.000689007	219.9997	219.9996
50	43	219.9995	0.000501568	0.000501568	219.9998	219.9997
51	44	219.9996	0.000365107	0.000365107	219.9999	219.9998
52	45	219.9997	0.000265782	0.000265782	219.9999	219.9999
53	46	219.9998	0.000193473	0.000193473	219.9999	219.9999
54	47	219.9999	0.000140839	0.000140839	219.9999	219.9999
55	48	219.9999	0.000102523	0.000102523	220	219.9999
56	49	219.9999	7.46315E-05	7.46315E-05	220	220
57	50	219.9999	5.43275E-05	5.43275E-05	220	220

Appendix: 4.E For explanation refer sections/subsection: 4.7, 4.7.2, 4.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	Proportional	0.36				
2	Integral	0.8				
3						
4	SP	220kV				
5				ABSOLUTE		
6	Iteration	PV	ERROR	ERROR	OUTPUT	INTEGRAL
7					0	0
8					0	0
9	1	0	220	220	79.2	63.36
10	2	0	220	220	142.56	126.72
11	3	0	220	220	205.92	190.08
1	4	79.2	140.8	140.8	240.768	230.6304
2	5	142.56	77.44	77.44	258.5088	252.9331
13	6	205.92	14.08	14.08	258.0019	256.9882
14	7	240.768	-20.768	20.768	249.5117	251.007
15	8	258.5088	-38.5088	38.5088	237.1438	239.9164

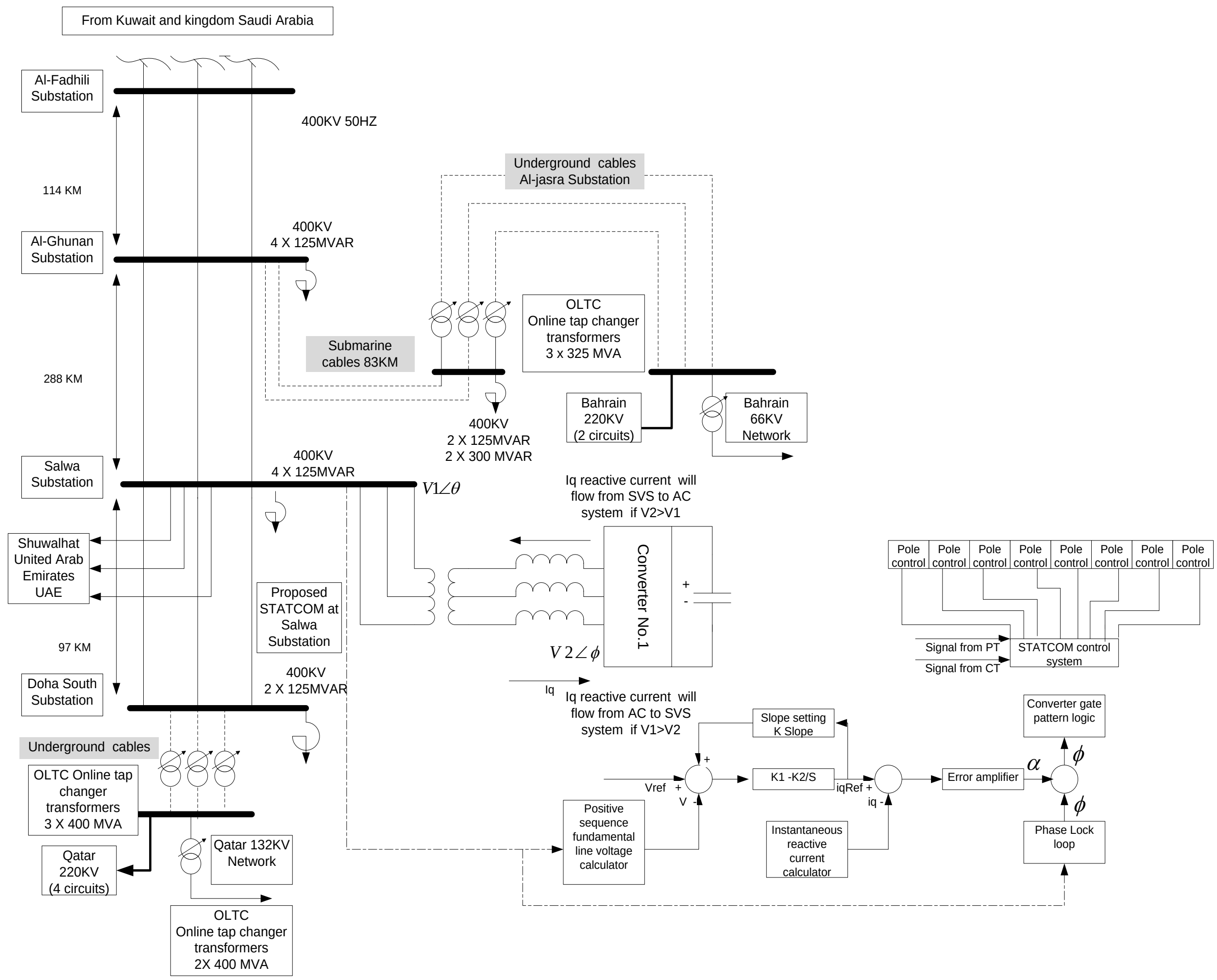
16	9	258.0019	-38.00192	38.00192	226.2358	228.9719
17	10	249.5117	-29.51168	29.51168	218.3477	220.4725
18	11	237.1438	-17.14381	17.14381	214.3008	215.5351
19	12	226.2358	-6.23575	6.23575	213.2902	213.7392
20	13	218.3477	1.652316	1.652316	214.334	214.2151
21	14	214.3008	5.699246	5.699246	216.2668	215.8565
22	15	213.2902	6.709762	6.709762	218.272	217.7889
23	16	214.334	5.665954	5.665954	219.8286	219.4207
24	17	216.2668	3.733192	3.733192	220.7646	220.4958
25	18	218.272	1.728024	1.728024	221.1179	220.9935
26	19	219.8286	0.171383	0.171383	221.0552	221.0429
27	20	220.7646	-0.764617	0.764617	220.7676	220.8226
28	21	221.1179	-1.117916	1.117916	220.4202	220.5007
29	22	221.0552	-1.055196	1.055196	220.1208	220.1968
30	23	220.7676	-0.767594	0.767594	219.9205	219.9757
31	24	220.4202	-0.420197	0.420197	219.8245	219.8547
32	25	220.1208	-0.120816	0.120816	219.8112	219.8199
33	26	219.9205	0.079543	0.079543	219.8485	219.8428
34	27	219.8245	0.175548	0.175548	219.906	219.8934
35	28	219.8112	0.188787	0.188787	219.9613	219.9477
36	29	219.8485	0.151453	0.151453	220.0023	219.9914
37	30	219.906	0.093983	0.093983	220.0252	220.0184
38	31	219.9613	0.038659	0.038659	220.0324	220.0296
39	32	220.0023	-0.002271	0.002271	220.0287	220.0289
40	33	220.0252	-0.025201	0.025201	220.0198	220.0217
41	34	220.0324	-0.032351	0.032351	220.01	220.0123
42	35	220.0287	-0.02875	0.02875	220.002	220.0041
43	36	220.0198	-0.019841	0.019841	219.9969	219.9983
44	37	220.01	-0.010009	0.010009	219.9947	219.9955
45	38	220.002	-0.001989	0.001989	219.9947	219.9949
46	39	219.9969	0.003084	0.003084	219.996	219.9958
47	40	219.9947	0.005259	0.005259	219.9977	219.9973
48	41	219.9947	0.005254	0.005254	219.9992	219.9988
49	42	219.996	0.004001	0.004001	220.0002	220
50	43	219.9977	0.00233	0.00233	220.0008	220.0006
51	44	219.9992	0.000817	0.000817	220.0009	220.0009
52	45	220.0002	-0.000245	0.000245	220.0008	220.0008
53	46	220.0008	-0.000796	0.000796	220.0005	220.0006
54	47	220.0009	-0.000922	0.000922	220.0002	220.0003
55	48	220.0008	-0.000775	0.000775	220	220.0001
56	49	220.0005	-0.000506	0.000506	219.9999	219.9999
57	50	220.0002	-0.000232	0.000232	219.9998	219.9999

Appendix: 4.F For explanation refer sections/subsection: 4.7, 4.7.2, 4.10 and 10.1

0	**A**	**B**	**C**	**D**	**E**	**F**
1	Proportional	0.38				
2	Integral	**0.9**				
3						
4	SP	**220kV**				
5				**ABSOLUTE**		
6	Iteration	**PV**	**ERROR**	**ERROR**	**OUTPUT**	**INTEGRAL**
7					0	0
8					0	0

9	1	0	220	220	83.6	75.24
10	2	0	220	220	158.84	150.48
11	3	0	220	220	234.08	225.72
1	4	83.6	136.4	136.4	277.552	272.3688
2	5	158.84	61.16	61.16	295.6096	293.2855
13	6	234.08	-14.08	14.08	287.9351	288.4702
14	7	277.552	-57.552	57.552	266.6004	268.7874
15	8	295.6096	-75.6096	75.6096	240.0557	242.9289
16	9	287.9351	-67.93512	67.93512	217.1135	219.6951
17	10	266.6004	-46.6004	46.6004	201.9869	203.7577
18	11	240.0557	-20.05573	20.05573	196.1366	196.8987
19	12	217.1135	2.886453	2.886453	197.9955	197.8859
20	13	201.9869	18.01307	18.01307	204.7308	204.0463
21	14	196.1366	23.86343	23.86343	213.1144	212.2076
22	15	197.9955	22.00446	22.00446	220.5693	219.7331
23	16	204.7308	15.26918	15.26918	225.5354	224.9552
24	17	213.1144	6.885573	6.885573	227.5717	227.3101
25	18	220.5693	-0.569312	0.569312	227.0937	227.1154
26	19	225.5354	-5.535431	5.535431	225.0119	225.2222
27	20	227.5717	-7.57172	7.57172	222.345	222.6327
28	21	227.0937	-7.09373	7.09373	219.9371	220.2067
29	22	225.0119	-5.0119	5.0119	218.3021	218.4926
30	23	222.345	-2.344992	2.344992	217.6015	217.6906
31	24	219.9371	0.062899	0.062899	217.7145	217.7121
32	25	218.3021	1.69786	1.69786	218.3573	218.2928
33	26	217.6015	2.398505	2.398505	219.2042	219.1131
34	27	217.7145	2.285493	2.285493	219.9816	219.8947
35	28	218.3573	1.642697	1.642697	220.5189	220.4565
36	29	219.2042	0.795784	0.795784	220.7589	220.7287
37	30	219.9816	0.018439	0.018439	220.7357	220.735
38	31	220.5189	-0.518937	0.518937	220.5378	220.5575
39	32	220.7589	-0.758912	0.758912	220.2691	220.298
40	33	220.7357	-0.735679	0.735679	220.0184	220.0464
41	34	220.5378	-0.537782	0.537782	219.842	219.8624
42	35	220.2691	-0.269116	0.269116	219.7602	219.7704
43	36	220.0184	-0.018396	0.018396	219.7634	219.7641
44	37	219.842	0.158005	0.158005	219.8241	219.8181
45	38	219.7602	0.239834	0.239834	219.9093	219.9002
46	39	219.7634	0.236598	0.236598	219.9901	219.9811
47	40	219.8241	0.175857	0.175857	220.0479	220.0412
48	41	219.9093	0.090724	0.090724	220.0757	220.0722
49	42	219.9901	0.009931	0.009931	220.076	220.0756
50	43	220.0479	-0.047904	0.047904	220.0574	220.0593
51	44	220.0757	-0.075697	0.075697	220.0305	220.0334
52	45	220.076	-0.076023	0.076023	220.0045	220.0074
53	46	220.0574	-0.057442	0.057442	219.9855	219.9877
54	47	220.0305	-0.030498	0.030498	219.9761	219.9773
55	48	220.0045	-0.004485	0.004485	219.9756	219.9758
56	49	219.9855	0.014454	0.014454	219.9813	219.9807
57	50	219.9761	0.02386	0.02386	219.9898	219.9889

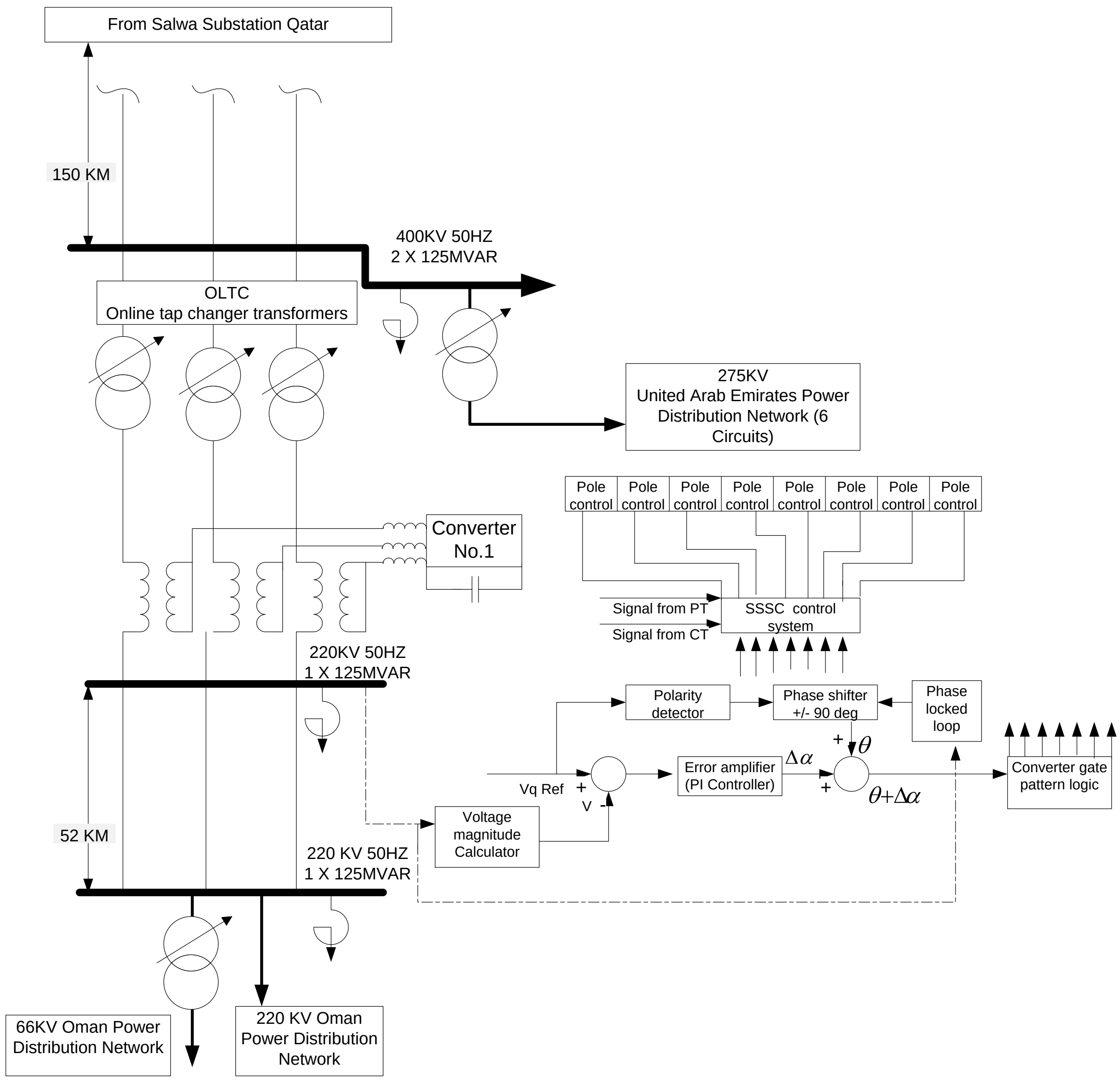
Appendix: 5.A: Proposed STATCOM Control Schematic in between Qatar and Bahrain Power system network and PI configuration parameters: **Refer sections/subsections: 4.7.1, 4.7.2, 4.8, 4.10, 5.1.3, 5.7, 10.1 and 10.5.1**



Capacitive and inductive mode of operations and control settings

S. No	DEVICE ID	DEVICE NAME	COUNTRYID STATIONID	CAPACTIVIE/INDUCTIVE CONTROL ID	P (POR)	I (INT)	REFERENCE VOLTAGE(KV)	MEASURED VOLTAGE (KV)	ERROR IN %
1	ST	STATCOM	S1/C1	CC1/LC1	0.32	0.6	400	+/- 392/408	+/-2%
2	ST	STATCOM	S1/C1	CC11/LC11	0.36	0.8	400	+/-384/416	+/-4%
3	ST	STATCOM	S1/C1	CC111/LC111	0.38	0.9	400	+/-376/424	+/-6%

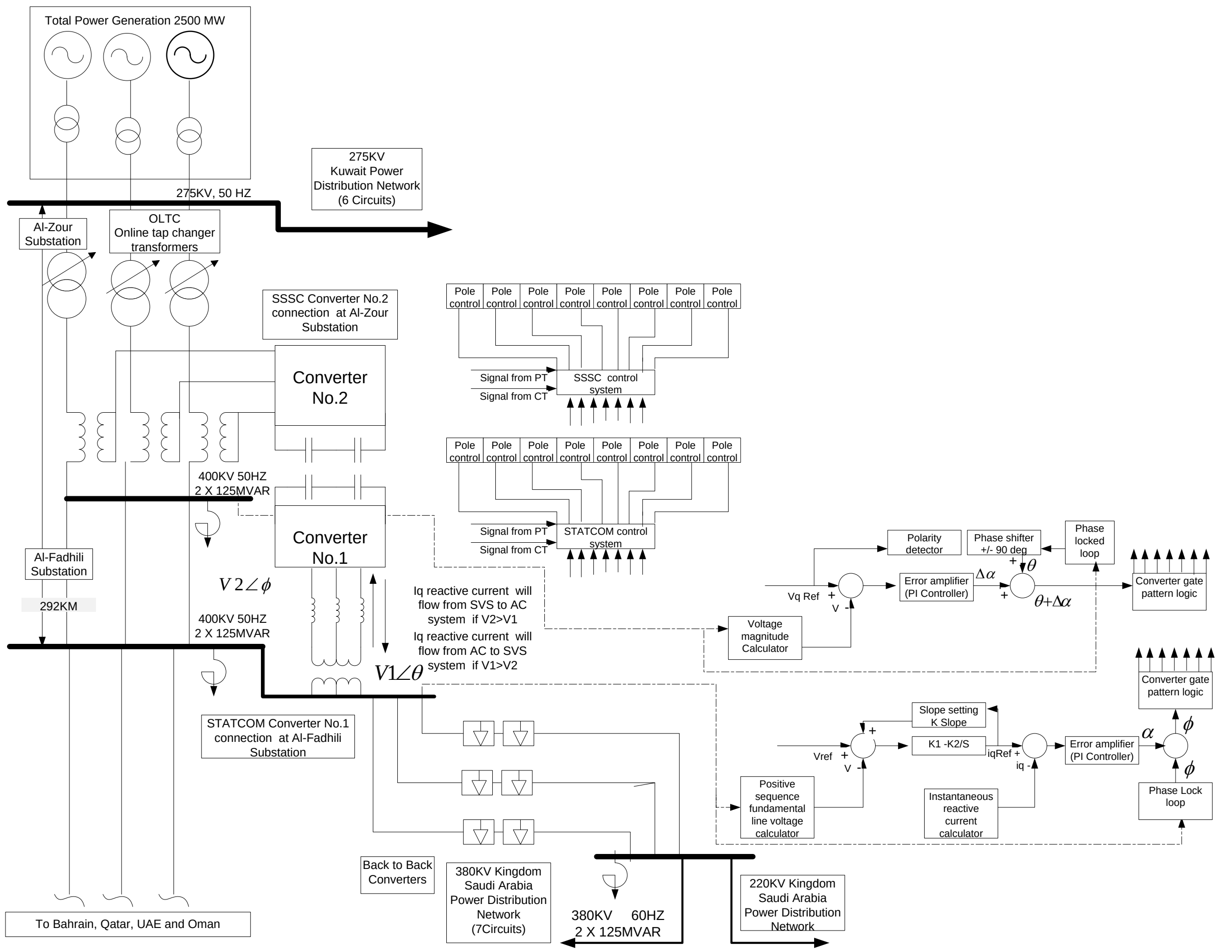
Appendix: 6.A proposed SSSC Control Schematic in between the Oman and United Arab Emirates power system network and PI configuration parameters: **Refer sections/subsections: 4.7.2, 4.8, 4.10, 6.1, 6.1.3, 6.7, 10.1 and 10.5.2**



Capacitive and inductive mode of operations and control settings

S.No	DEVICE ID	DEVICE NAME	COUNTRYID STATIONID	CAPACTIVIE/ INDUCTIVE CONTROL ID	P	I	REFERENCE VOLTAGE(KV)	MEASURED VOLTAGE (KV)	ERROR IN %
1	SS	SSSC	S7/C7	CC2/LC2	0.32	0.6	220	+/-215/225	+/-2
2	SS	SSSC	S7/C7	CC22/LC22	0.36	0.8	220	+/-211/229	+/-4
3	SS	SSSC	S7/C7	CC222/LC222	0.40	0.9	220	+/-206/233	+/-6

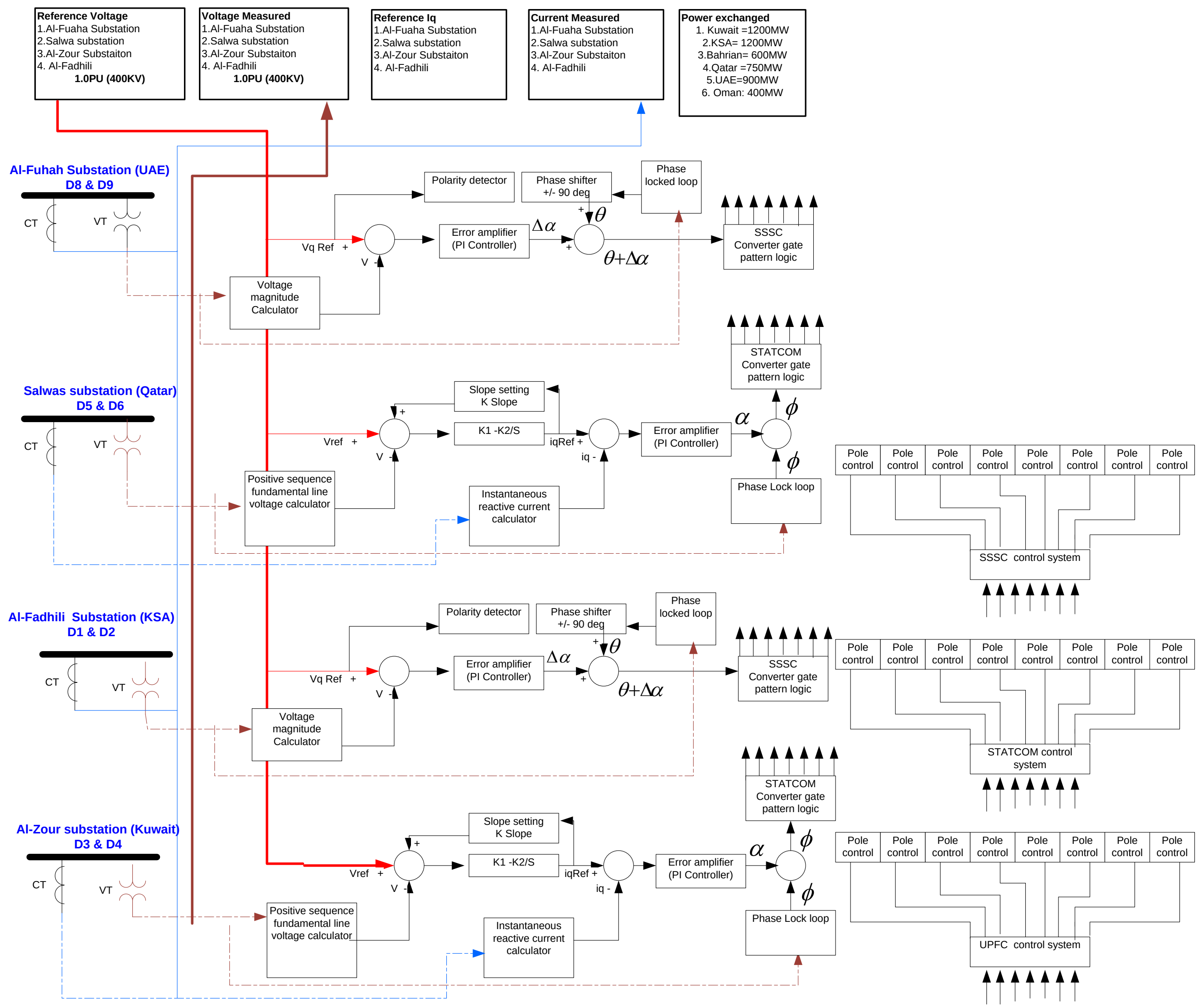
Appendix: 9.A proposed UPFC Control Schematic in between the Kingdom Saudi Arabia and Kuwait power system network and PI configuration parameters: **Refer sections/subsections: 4.7.1, 4.8, 4.10, 17.1.3, 7.8, 10.1 and 10.5.3**



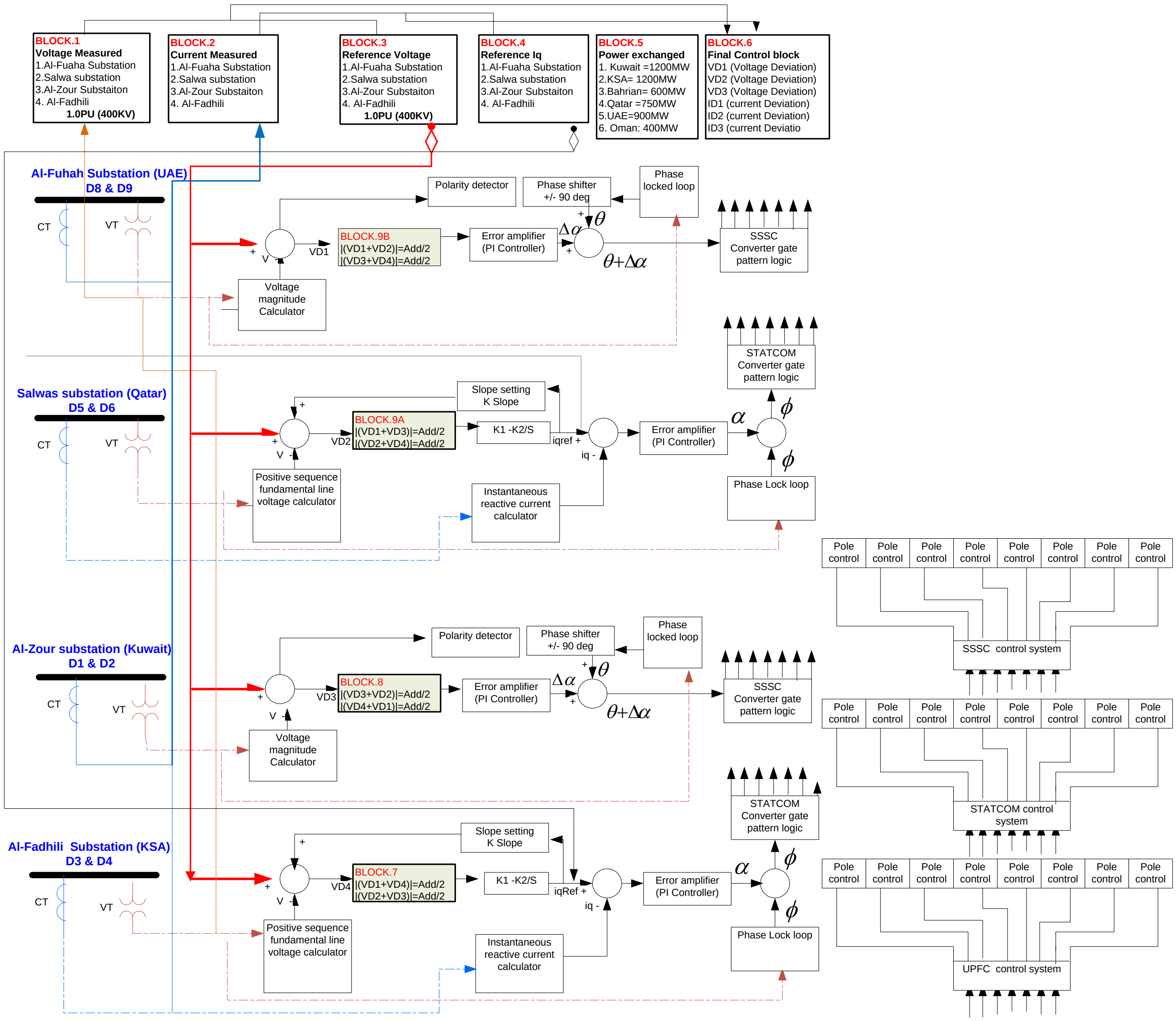
Capacitive and Inductive mode of Operations Settings

S.No	DEVICE ID	DEVICE NAME	COUNTRY ID STATIONID	CAPACTIVIE CONTROL ID	P	I	REFERENCE VOLTAGE(kV)	MEASURED VOLTAGE (kV)	ERROR IN %
1	UP	UPFC	S6/C6	CC3/LC3	0.32	0.6	400	+/-392/408	+/-2
2	UP	UPFC	S6/C6	CC33/LC33	0.35	0.8	400	+/-384/416	+/-4
3	UP	UPFC	S6/C6	CC333/LC333	0.40	0.9	400	+/-376/424	+/-6

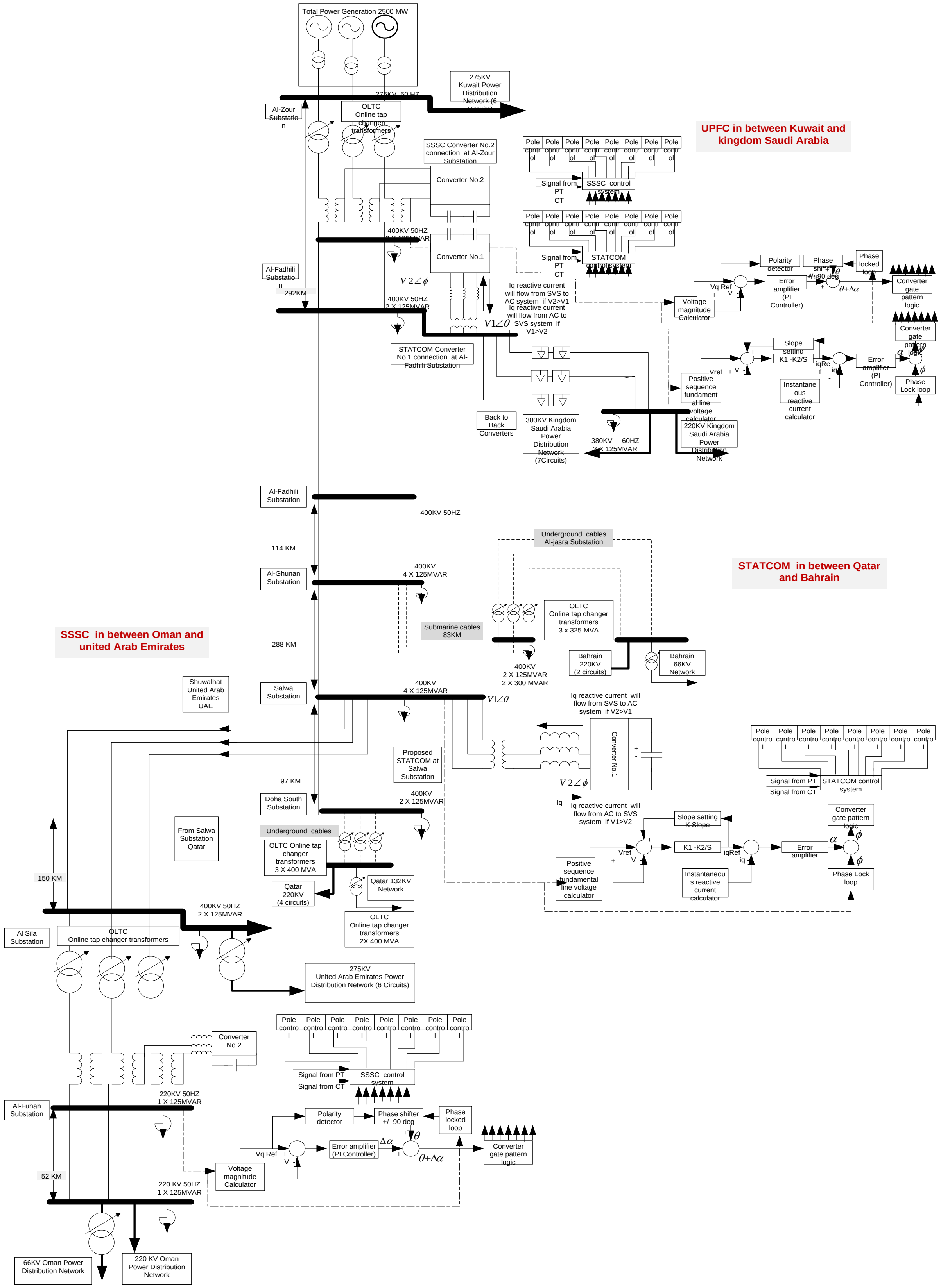
Appendix: 9.A (De-centralized control configuration and implementation to control and monitor all FACTS devices operations at GCC Power Grid)**: Refer in section 9.7 (Internal local control loop) in chapter 9.**



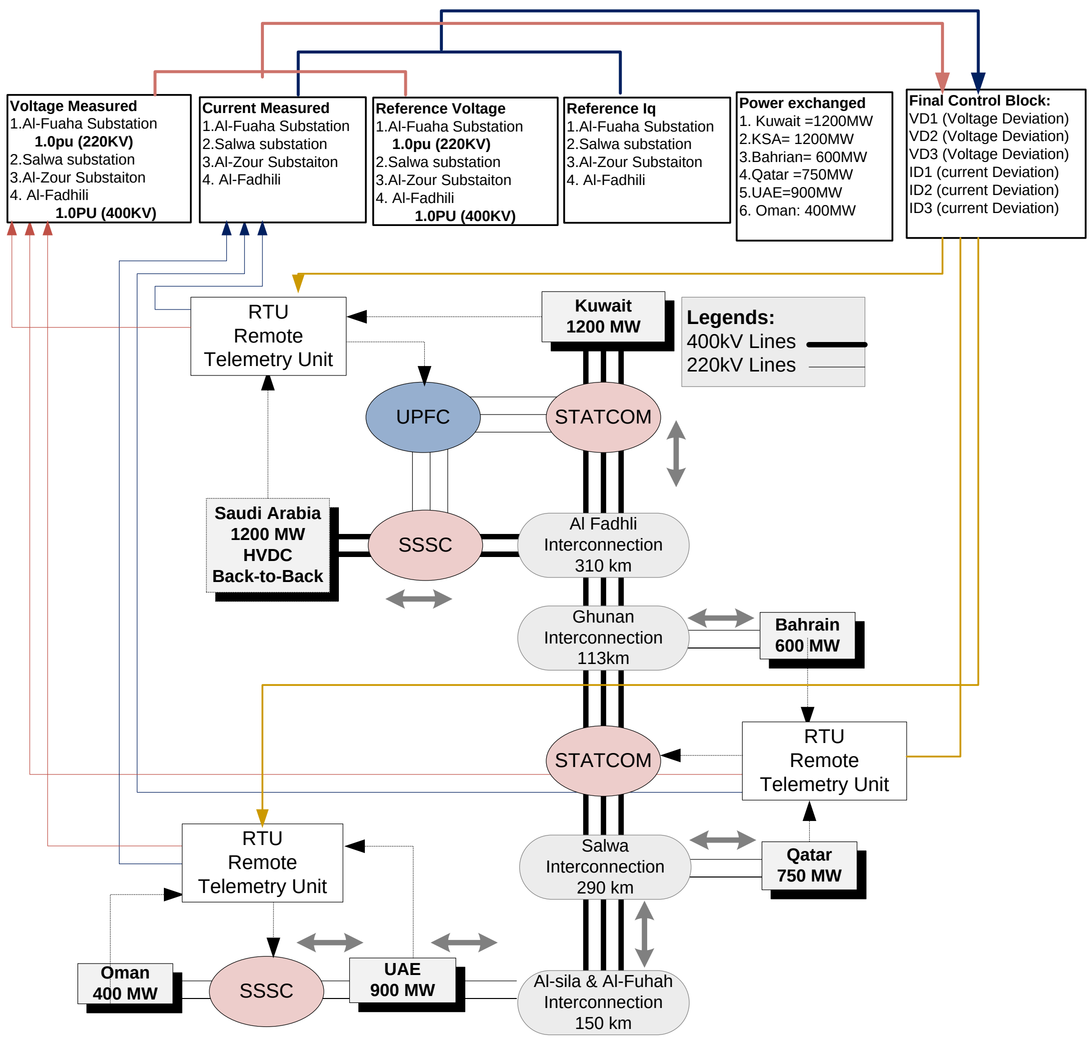
Appendix: 9.B (Centralized control configuration and implementation to control and monitor all FACTS devices operations at GCC Power Grid)**: Refer in section 9.8 (External or remote control loop) in chapter 9.**



Appendix: 9.C (STATCOM, SSSC and UPFC devices are integrated stringently to improve power system's operations at GCC power grid). **Refer in section 9.9 in chapter 9.**



Appendix: 9.D (FACTS-FRAME control schematic) Refer section/subsections 4.7.2, 9.12.4, 10.1



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Novelties and Contributions of this thesis

In the past, there were large numbers of research papers published related to FACTS devices operations, control and protection systems at different levels. In this research work FACTS controller based three novelties have been introduced and described as below.

The first novelty of this research work is a FACTS-FRAME that has been introduced to integrate a centralized and decentralized control system to operate the STATCOM, SSSC & UPFC control devices at different locations on the GCC power grid. The simulation results demonstrate that this centralized controller has a capacity and capability to adjust STATCOM, SSSC and UPFC devices operating parameters to maintain all three devices operations in parallel in order to meet time-based required reactive power compensation on the GCC power grid.

Similarly, the decentralized controller has a capacity and capability to adjust the STATCOM, SSSC and UPFC devices operating parameters to maintain all three devices operations independently in order to meet time-based required reactive power compensation at their define location on the GCC power grid. The primary aim of both control topologies is to address time based power transmission system contingences on the GCC power grid. The second novelty of this work is to operate these devices seamlessly through three control limits which have been introduced based on PI controller's three sets of tuning parameters by using a D. J. Cooper control optimization technique. Based on these parameters each FACTS controller will adjust compensation (capacitive & inductive), in three control limits firstly minimum +/- 2%, secondly medium +/- 4%, thirdly maximum +/- 6%. These control limits have demonstrated robust operations at different locations on the GCC power grid. The third novelty of this work is the FACTS devices selection process by using the WBD iteration based value estimation technique.

This is a simple technique which has a substantial potential particularly for technology selection processes compare to genetic algorithm selection processes. In the WBD selection process proved practical and theoretical parameters are applied. These are used for assessments to identify and determine the estimated value credibility of each parameter in order for the right decision to be made by the technical committee. This is the main strength of the WBD selection process technique which used proved practical results. But it is very tedious and difficult to find the right people for the assessment and technical committee. This is a weakness of the WBD technique. Listed below chapters indicates the contribution of this thesis.

Chapter no 1 in this chapter we have

1. Provided Power transmission system network problems
2. Provided GCC power transmission current operations
3. Provided challenges on the GCC power grid
4. Provided why HVDC and FACTS devices needed.

Chapter no 2 in this chapter we have

1. Provided STATCOM, SSSC and UPFC application in the world
2. Provided Current project in operations of HVDC and FACTS controllers

Chapter no 3 in this chapter we have

1. Provided long transmission line model, its characteristics
2. Provided line inductive and capacitive reactance

3. Provided line inductance balance for three phase line
4. Provided basic principle of shunt compensation
5. Provide shunt inductive and capacitive mode of compensation
6. Provided degree of shunt compensation
7. STATCOM mode of operations
8. STATCOM Benefits
9. Provided basic principle of series compensation
10. Provide series inductive and capacitive mode of compensation
11. Provided degree of series compensation
12. SSSC mode of operations
13. SSSC benefits
14. Provided basic principle of UPFC compensation
15. UPFC operations
16. UPFC benefits
17. Provided objective of HVDC transmission line
18. HVDC link deliverables
19. Provided challenges of HVDC
20. Provided FACTS devices outcomes
21. HVDC outcomes
22. Provided Economics consideration of FACTS devices and HVDC
23. Provided HVDC and FACTS devices benefits

Chapter no 4 in this chapter we have

1. Provided PID, PI, PD controller scope of functionality
2. Provided PI controllers tuning framework
3. Provided PI controller simulation technique

Chapter no 5 in this chapter we have

1. Provided STATCOM application reinforcement plan in between Qatar and Bahrain
2. Provided STATCOM controller selection process
3. Provided STATCOM model results
4. Provided network response with and without STATCOM

Chapter no 6 in this chapter we have

1. Provided SSSC application reinforcement plan in between UAE and Oman
2. Provided SSSC controller selection process
3. Provided SSSC model results
4. Provided network response with and without SSSC

Chapter no 7 in this chapter we have

1. Provided UPFC application reinforcement plan in between KSA and Kuwait
2. Provided UPFC controller selection process
3. Provided UPFC model results
4. Provided network response with and without UPFC

Chapter no 8 in this chapter we have

1. Provided HVDC design criteria
2. Provided transmission capacity of HVDC
3. Provided performance of HVDC system
4. Provided Rectifier control and operations
5. Provided inverter control and operations

Chapter no 9 in this chapter we have

1. Provided FACTS-FRAME Architecture
2. Provided FACTS-FRAME configuration
3. Provided FACTS devices optimal locations
4. Provided internal and external control of the FACTS devices
5. Provided FACTS controller integration and results

Chapter no 10 in this chapter we have

1. Provided PI controller configuration parameters selection process & significance
2. Provided Internal and external controls significance:
3. Provided Operational and maintenance control significance
4. Provided FACTS devices selection process & significance
5. Provided STATCOM, SSSC & UPFC controllers significance

Chapter no 11 in this chapter we have presented

A framework for implementation of FACTS devices on the GCC power grid has been investigated to achieve following benefits:

1. Increased power transfer capability on the GCC power grid.
2. Increased power transfer capability
3. Improved GCC power grid operational reliability
4. Improved GCC power grid controllability

Bibliography

Tariq Masood (SM'03) received the M.Eng in Electrical power system engineering from the University of Bath, Bath, UK., in 2007 and proceeding to Ph.D. in Electrical power system (FACTS/HVDC control devices) from the University of Bath, Bath, UK. He is a Chartered Engineer and Senior Member of the IEEE-USA and Member of the IET-UK. He is also certified member of the CET International USA and registered member of the ASCET (American Society of Certified Engineers and Technicians) USA. He has also delivered numerous lectures on FACTS Technology at IEEE Qatar Section and various Universities including University of Bath, Bath, UK. He is also Lean Six-Sigma Green belt certified. He joined the Qatar Petroleum since 1997 where he is currently Production Data analyst. He is/has been on several production department technical and management committees' member. He has published 15 technical papers in IEEE Conference, Honeywell Users group and other International Conferences. He is the Secretary/Treasurer of the IEEE Qatar Section. He received several awards in recognition of his outstanding performance and dedication to improve Qatar Petroleum production operations and control. He was the secretary for the GCC oil producing companies (QP-Qatar, PDO-Oman ARAMCO-Saudi Arabia, KOC-Kuwait, TATWEER-Bahrain, and ADNOC-United Arab Emirates) Production and Maintenance Technical Committee in 2008 and 2011.

Published papers and Seminars

1. **Tariq Masood,** R.K. Aggarwal, S.A. Qureshi, , R.A.J Khan STATCOM and SVC Control Operations and Optimization during Network Fault Conditions: **IEEE International Symposium on Industrial Electronics Bari_ Italy (04-07 July, 2010).**

2. **Tariq Masood**, R.K. Aggarwal, S.A. Qureshi, , R.A.J Khan STATCOM Model against SVC Control Model Performance Analyses Technique by Matlab**: (ICREQP,10 Granada Spain 23-25 March,10).**

3. **Tariq Masood**, R.K. Aggarwal, S.A. Qureshi, , R.A.J Khan STATCOM Control Reconfiguration Technique for Steady State and Dynamic Performance Optimization during Network Fault Conditions: **(ICREQP,10 Granada Spain 23-25 March,10).**

4. **Tariq Masood**, S. A Qureshi, A.j Khan, Nasser Elamedi, Yacob Y.Almulla, S K Shah "Facts Control Devices (Statcom, Sssc And Upfc) Re-Configuration Techniques By Psim/Matlab" **Papers published ICEE2007 on 11-12th April, 2007 at UET/RCET Lahore _ Pakistan**

Seminars delivered on FACTS Technology following University:

1. University of Bath, Bath, UK in May 03, 2010
2. Texas A & M University, Qatar Campus in October 11, 2012
3. Qatar University, Doha Qatar, October 14, 2012
4. Texas Tech University, Lubbock, USA in November 05, 2012