UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

COMPARISON OF TECHNIQUES FOR VOLTAGE CONTROL AND POWER SYSTEM STABILITY IN THE NORTH OF IRAQ

M.Sc. THESIS
IN
ELECTRICAL AND ELECTRONICS ENGINEERING

BY
AYOOB MUSTAFA ALEE

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Comparison of Techniques for Voltage Control and Power System Stability in the North of Iraq

M.Sc. Thesis
in
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Supervisor
Prof. Dr. Ergun ERÇELEBİ

By
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This is to certify that we have read this thesis and that in our opinion; it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Ayoob Mustafa ALEE

ABSTRACT

COMPARISON OF TECHNIQUES FOR VOLTAGE CONTROL AND POWER SYSTEM STABILITY IN THE NORTH OF IRAQ

ALEE, Ayoob Mustafa

M.Sc. in Electrical and Electronics Engineering

Supervisor: Prof. Dr. Ergun ERÇELEBİ

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Power flow and voltage control are a vital role in the north of Iraq's electrical power system. This thesis illustrates the potential applications of flexible AC transmission system (FACTS) controllers, such as the static VAR compensator (SVC) and the Static synchronous compensator (STATCOM) for the control of voltage and power flow, and improving the voltage regulation. The STATCOM and SVC are used in 132 kV Soran substation. Based on, a back to back connected thyristor valves and voltage-source converter, SVC and STATCOM regulate system voltage by generating or absorbing reactive power. The objective is to define the reactive power generated and voltage control at 132 kV Soran substation using STATCOM and SVC. Finally, in case, our study has compared the STATCOM with SVC in static voltage stability improvement. Different performance measures have been considered under different operating system conditions for the north of Iraq's electrical power system. The results show that STATCOM has better performance over SVC.

Keywords: SVC, STATCOM, Voltage control and power system stability, power flow control.

ÖZET

IRAK'IN KUZEYINDEKI GERİLİM KONTROL VE GÜÇ SİSTEMİ İSTİKRAR İÇİN TEKNİKLERİ KARŞILAŞTIRILMASI

ALEE, Ayoob Mustafa
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Kuzey Irak'ın elektrik güç sisteminde güç akışı ve gerilim kontrolü hayati bir rolü vardır. Bu tez gerilim ve güç kontrolü ve gerilim regülasyonu iyileştirmek için esnek AC iletim sistem denetleyicilerimin potansiyel kullanımlarını açıklar. Statik senkron kompensator (STATCOM) ve statik VAR kompensator (SVC) 132kV Soran santralinde kullanılmaktadır. Arka arkaya bağlı tristör vanalarına dayalı ve gerilik kaynak dönüştürücü, SVC ve STATCOM reaktif gücü üreterek veya harcayarak sistem gerilimini düzenlemektedir. Amaç üretilen reaktif gücü ve gerilim kontrolünü 132kilo voltluk Soran santralinde STATCOM ve SVC kullanarak tanımlamaktır. Son olarak çalışmamız STATCOM ile SVC'yi statik gerilim kararlılığı iyileştirme açısından karşılaştırdı. Kuzey Irak'ın elektrik güç sistemi için farklı performans ölçümleri farklı işletim sistem şartları altında ele alındı. Sonuçlar STATCOM'un SVC'ye göre daha iyi performansı olduğunu gösterdi.

Anahtar Kelimeler: SVC, STATCOM, Gerilim kontrolü ve güç sistem istikrarı, güç akış kontrolü.

Dedicated to:

My Country, Beloved Parents and my all Family.

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I would like First of all to thank Almighty Allah, the most gracious and the most merciful. I would like to thank Prof. Dr. ERGUN ERÇELEBI Head of Electrical & Electronic Engineering Department, and my project supervisor, for his support, guidance, motivation and encouragement throughout the period this work was carried out. I do not have sufficient words to thank my first ever teachers and my parents. I would like to offer my sincere thanks to all my family. I am also thankful to Mr. Twana Salahaddin for his valuable suggestions towards the completion of my project. I take this occasion to express my gratitude to the people who have been instrumental in the successful conclusion of this thesis. Finally, I have to give my deepest appreciation to all ministries in the north of Iraq that supported me to complete the Master degree.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

LIST OF SYMBOLS/ABBREVIATIONS

$	Dollar
AC	Alternating current
B	Susceptance in mho
B1, 2	Bus 1, 2…
Bref	Susceptance reference
C	Capacitor
Cos	cosine
DBK/HPS	Derbandekhan hydro power station
DC	Direct current
DCL	Double Circuit - Single Lark Conductor
DCT	Double Circuit - Single Teal Conductor
DCTL	Double Circuit - Twin Lark Conductor
DCTT	Double Circuit - Twin Teal Conductor
Deg	Degree
DGPP	Duhok generation power plant
DOK/HPS	Dokan hydro power station
EGPP	Erbil generation power plant
FACTS	Flexible alternating current Transmission System
FC	Fixed Capacitor
FVSI	Fast Voltage Stability Index
GTO	Gate Turn Off
HV	High Voltage
Hz	Hertz
I	Current
Id	direct-axis current
IEEE	Institute of Electrical and Electronics Engineers

IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
Im	Imaginary
Ip	Active Current
IPFC	Interline Power Flow Controller
Iq	quadrature-axis current
Iq	Reactive Current
IR	Receiving Current
IS	Sending Current
Kf	feed forward gain
Ki	integral gain
Km	kilometer
Kp	proportional gain
KR	Kurdistan region
KRPS	Kurdistan Regional Power System
KV	Kilovolt
KVA	Kilovolt ampere
L	Inductance in Henry
LP	Low pressure
LV	Low voltage
MATLAB	Matrix Laboratory
MSC	Mechanically-Switched Capacitor
MSR	Mechanically-Switched Reactor
MVA	Mega volt-ampere
MVAR	Megavolt Ampere Reactive
MW	Megawatt
P	Active power
P.F	Power Factor
P.u	per unit
PI	proportional–integral controller
PLL	phase-locked loop
P-Q buses	Active-Reactive buses
Pref	Reference power

PSAT	Power System Analysis Toolbox
PST	Phase Shift Transformer
P-V buses	Active-Volt buses
PV curve	power-volt curve
PWM	Pulse width modulation
Q	Reactive power
QD	Demand reactive power
QR	Receiving reactive power
Qref	references Reactive power
QV curve	Reactive-volt curve
R	Resistance in Ohm
Re	Real
RMS	root-mean-square
S	Apparent power
s	second
SCC	Self-commutated compensator
SCL	Single Circuit - Single Lark Conductor
SCT	Single Circuit - Single Teal Conductor
SCTT	Single Circuit - Twin Teal Conductor
SGPP	Sulymaneah generation power plant
SMIB	Single Machine Infinite Bus
SSR	Sub-Synchronous Resonance
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
STATCON	Static Synchronous Condenser
SVC	Static VAR Compensator
T	Periodic time
T.L	Transmission line
TCPAR	Thyristor Controlled Phase Angle Regulator
TCPS	Thyristor Controlled Phase Shifting Transformer
TCPS	Thyristor Controlled Phase Controlled Transformer
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Compensator

TCSR	Thyristor Controlled Series Reactor
Td	time delay due to thyristor valves firing
THD	Total Harmonic Distortion
TSC	Thyristor-Switched Capacitor
TSOs	Transmission System Operators
TSR	Thyristor-Switched Reactor
TSSC	Thyristor-Switched Series Capacitor
TSSR	Thyristor-Switched Series Reactor
ULTC	under load tap changer
UPF	unity power factor
UPFC	Unified Power Flow Controller
V	Volt
V1	primary voltage
VA	Volt Ampere
Vac	voltage Alternating current
VAR	Volt Ampere Reactive
VAV	Average voltage
Vd	direct-axis voltage
Vd	Voltage drop
Vdc	voltage Direct current
Vm	measured voltage
VP	peak voltage
VP-P	peak-to-peak voltage
Vq	quadrature-axis voltage
VR	Receiving voltage
Vref	Reference voltage
VREF	reference Voltage
VS	Sending voltage
VSC	Voltage Source Convertor
VSI	voltage source inverter
W	Watt
X	Reactance in ohm
Xs	Slope or droop reactance
Z	Impedance

CHAPTER 1

INTRODUCTION

Chapter one is a general introduction to presenting a master thesis, comparison of two techniques (STATCOM and SVC) for voltage control and power system stability in the north of Iraq's electric power system, with background and structure of the north of Iraq's electrical power system. Finally, express some literature review.

1.1 Background

The main high voltage level in the north of Iraq's power system is 132kV, which was interconnected all the buses after 2005. Before 2005, the main power supply were from the two hydropower plants in the north of Iraq such as DOK/HPS and DBK/HPS and Iraqi central grid. Duhok was supplied from Turkey and Iraqi central grids. Four years ago electricity sector got the big share of a government fund to build up the network to reconnect all the provinces together and renew the old power system network. As an investment, new (gas and heavy fuel) power plants have been built relatively near each province center to meet the rapid increase in demand. The rate of electricity shortages have been minimized but still the level of voltage is not sustained. The problem of high reactive power loads still exists in this network especially during winter and summer season, in which the voltage is very low. Now in practically to compensate voltage sag usually, transformers tap changers and capacitor banks are in use at substations to increase distribution voltage level. Still, the voltages at customer side are lower than the allowable value for which have a bad impact on the system [1]. In my thesis, to improve the above problem, I would like to use two modern techniques. Then show the effects and compared with each other's two modern methods.

1.2 Problem Statement and Contribution of Thesis

Inductive load or long distance transmission line because that receiving voltage in the north of Iraq's power system lessens and complex power flow incredibly. Voltage control and reactive power flow management in the north of Iraq's power system are two aspects of a single activity that both props supports reliability and facilitates commercial transactions across transmission line networks. On a 132kv Soran station, voltage is controlled by managing production and absorption of reactive power under STATCOM and SVC supervision controllers. This thesis contains contributions of novel reactive power control and voltage stability schemes for transmission lines in the north of Iraq. Reactive power compensation is done for; reduction of KVA demand, reduction in system losses, better efficiency of power generation (transmission and distribution), improvement in voltage profile, improves system power factor, higher load capability, increases system capacity and saves cost on new installations.

1.3 Aims of the Thesis

1. General introduction to the electric power system in the north of Iraq and present power system's problem.
2. improvement the voltage levels and operate the power system within the allowable range.
3. Increase transmitting active power thereby active power losses in transmission will be decrease.
4. Decrease transmitting reactive power thereby reactive power losses in transmission will be decrease.
5. The current at the node bus FACTS connection is an increase, by inject current.
6. Answer below question. How we can improve and control receiving voltage, active and reactive power flow?
7. Well known techniques (SVC and STATCOM) for voltage control and power system stability in the north of Iraq's grid.
8. Using shunt reactive power controllers, STATCOM and SVC in the north of Iraq's power system to minimize the reactive power flow. Thereby improving voltage stability and increases the quality of power in many fields for all buses.
9. Compared effects of STATCOM with SVC controllers to voltage control and increase transmitting active power in the north of Iraq's power system at Soran 132KV substation before fault, during fault, after fault. Then compared results without a controller.
10. Finally, compare the active and reactive power flow, voltage and current between some buses, when suddenly increase load.

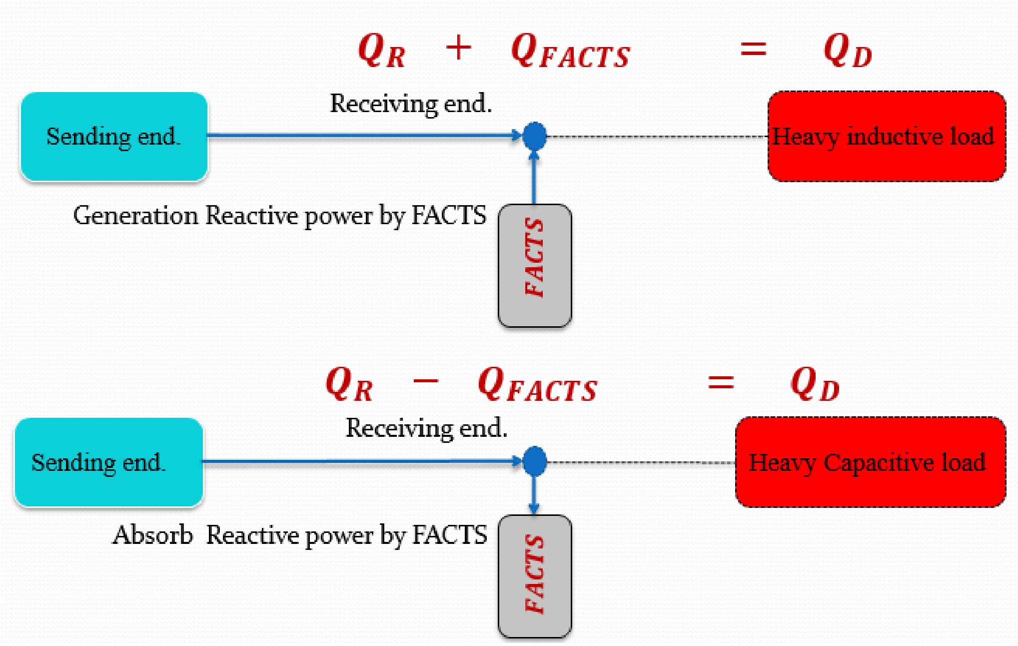


Figure 1.1 Reactive power compensation.

1.4 The North of Iraq's Electric Power System Description

The north of Iraq power system is a network that show in figure 1.2 of electrical components used to generate, transmit and use electric power. The power system can be extensively divided into three main components. Generation system, transmission system, and distribution system. In the north of Iraq, the transmission lines high voltage level is 132kV.which connects nine power plant generation and 101 substations (46 stationary substations and 55 mobile substations) in each province together. The transmission system is an overhead line; there are some new underground cables. Distribution voltage level is 33kV, 11kV, and consumer voltage level is 380V for three phases and 220V for single phase. In this thesis, main voltage is taken for study because the main grid itself distresses from unacceptable level voltage.

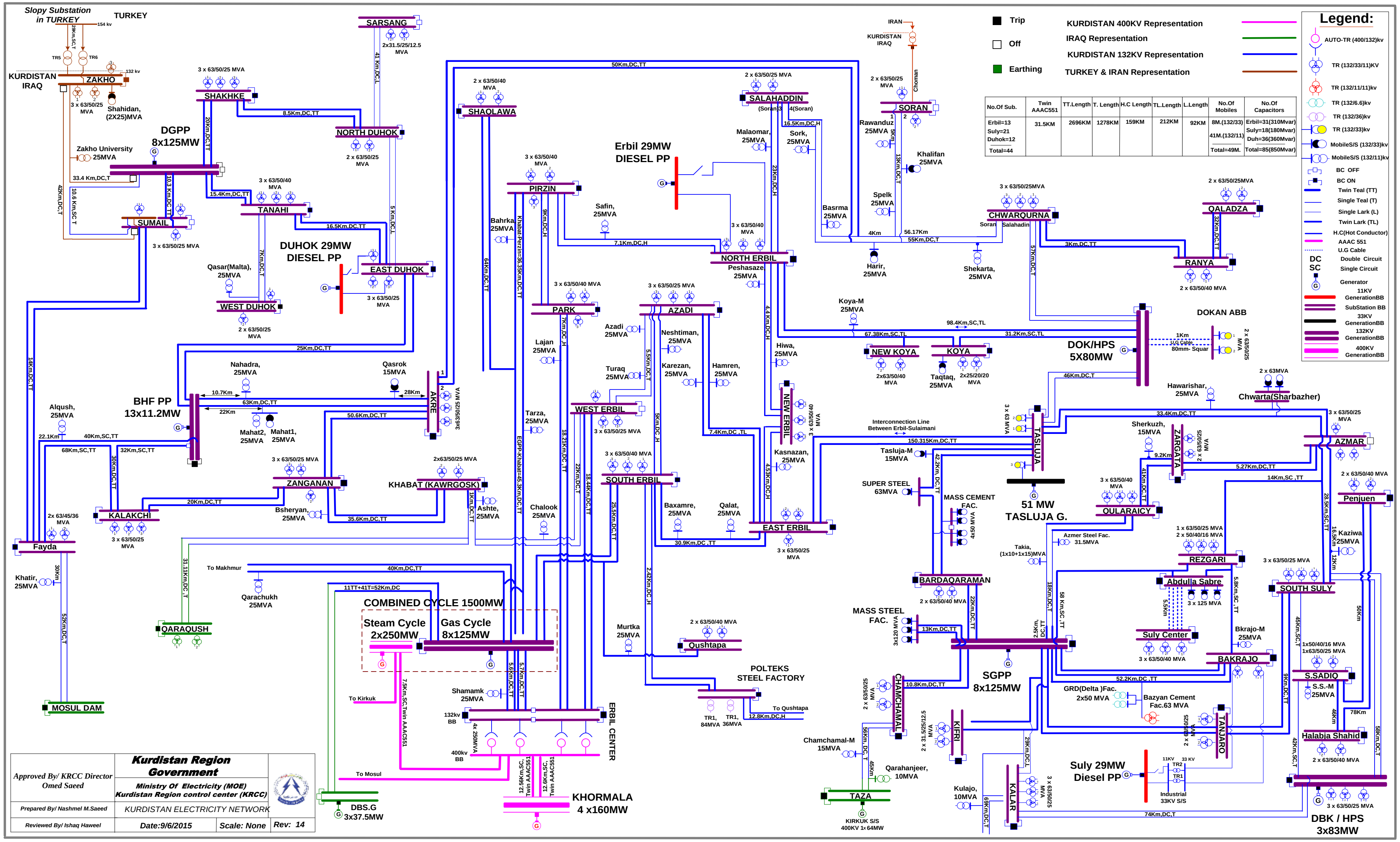


Figure 1.2 Single line diagram network power system in the north of Iraq. [KR Ministry of Electricity]

1.4.1 Power Plants (Generation system)

The generators that supply the power to the consumer, mainly by synchronous generators driven by prime mover working on various forms of energy. At the generating station, the voltage is stepped up to transmit the power and by reducing losses. The north of Iraq's power system network consists of 9 power plants located in different locations in each province. More details about their types and capacity are given in table1.1 [1]

Table1.1 Data of power plants generation. [KR Ministry of Electricity]

Name of P.P	Type of PP	Units	Max.MW	Min.MW	Max.Mvar	Min.Mvar	R(ohm)	L(H)	VL-L
Erbil 29 MW	Diesel	4	7	1.75	3.6	-3.6	0	0.5549	132 KV
Suly. 29 MW	Diesel	4	7	1.75	3.6	-3.6	0	0.5549	132 KV
Duhok29 MW	Diesel	4	7	1.75	3.6	-3.6	0	0.5549	132 KV
BHF	Heavy Fuel	13	11.2	2	2.4	-2.4	0	0.5549	132 KV
DBK/HPS	Hydro	3	83	20	24	-2.4	0.709	0.113	132 KV
DOK/HPS	Hydro	5	80	30	18	-18	0.588931	0.09377	132 KV
DGPP	Diesel or Gas	8	135	40	67	-67	0.52272	0.075	132 KV
SGPP	Diesel or Gas	8	135	40	67	-67	0.52272	0.075	132 KV
EGPP	Diesel or Gas	8	135	40	67	-67	0.52272	0.075	132 KV

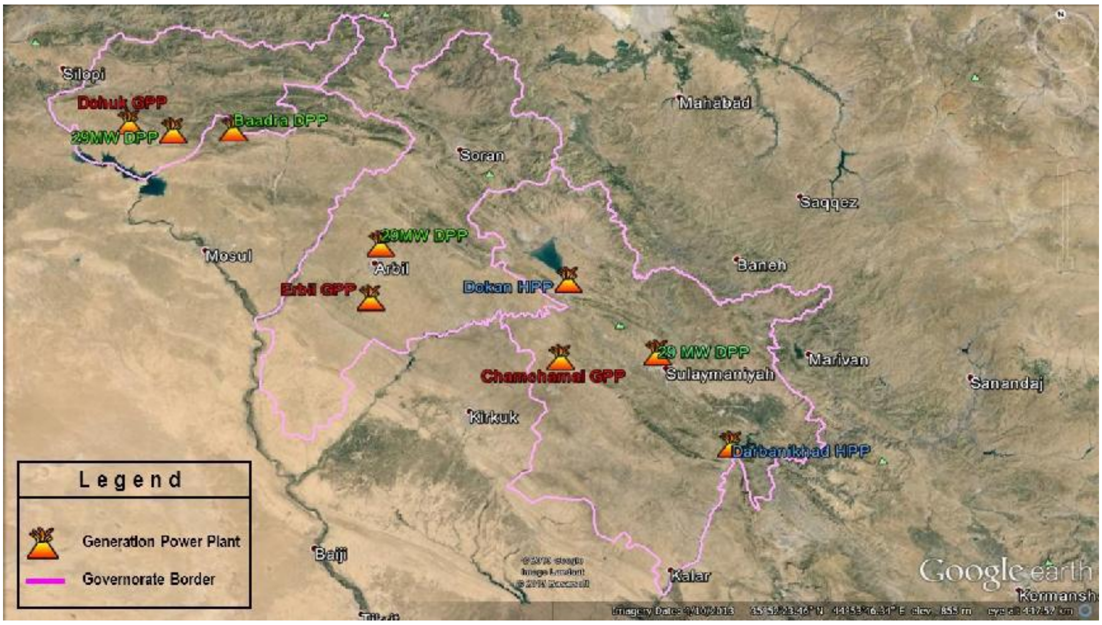


Figure 1.3 the north of Iraq's power plant locations [1]

1.4.2 132kv Substations

The north of Iraq's electrical power system consists of 101 132kV substations; they are 46 stationary Substations and 55 mobile substations. Which steps down transmission voltage further and then distribution system that feeds the power to nearby demands and industries. Appendix X has more detail of these substations.

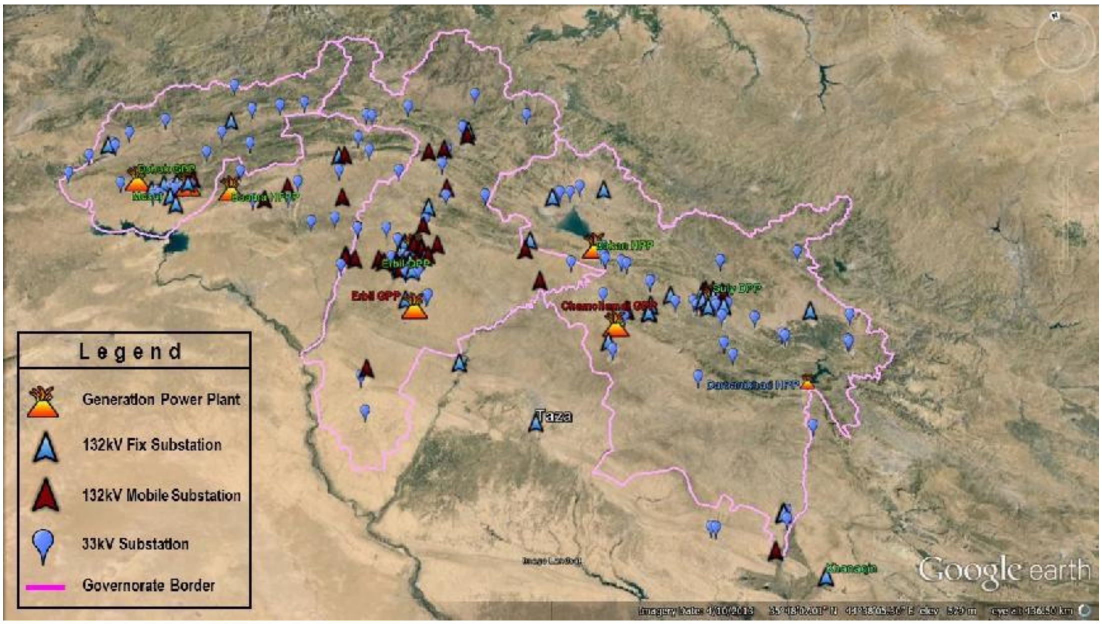


Figure 1.4 the north of Iraq's power plant and substation locations [1]

1.4.3 Transmission Lines (T.L)

The transmission lines are closed system that carries the power from the generating center to a destination. They are the main part of the power system that contains the bulk of power [2]. Transmission lines role is increased by reactive power compensation [3]. The north of Iraq electrical network consist many types of overhead transmission such as:

- Single Circuit - Single Lark Conductor SCL,
- Single Circuit - Single Teal Conductor SCT,
- Single Circuit - Twin Teal Conductor SCTT,
- Double Circuit - Single Lark Conductor DCL,
- Double Circuit - Single Teal Conductor DCT,
- Double Circuit - Twin Lark Conductor DCTL and
- Double Circuit - Twin Teal Conductor DCTT)

They connect the generating station to the grid. Transmission lines should be done in such a way to be minimum losses.which their rating capacities, and technical parameters are given in Appendix y

Figure 1.5 Single circuit - double lark or teal conductor.

[http://www.alibaba.com/product-detail/132kv-230kv Electric_60167733942.html]

Figure 1.6 Double circuit - twin teal or lark conductor

[http://www.bbc.com/news/uk-32234656]

1.4.4 Capacitor Banks

Capacitors are two conductor layers separated by an insulating layer [4]. Capacitors are compensation devices that simplest and most effective ways of generating and having a tendency to manage or control reactive power [5]. They can be placed virtually anywhere in the power system where needed. the square of the voltage is proportional to output of capacitors and conductors. Usually, capacitor banks are set aside at stationary type substations at low side voltage (33kV or 11kV sides). Those capacitor banks are switched through a circuit breaker [1]. List of capacitor banks in the north of Iraq power system is given in Appendix z.

1.4.5 Loads

The load is the final stage in the delivery of electricity to end users [6]. Mainly loads absorb reactive power [7]. Voltage stability is strictly related to load quality, the reactive power using up of the load has a great sag on voltage profile at the bus. The response of loads to voltage changes happening over many minutes can affect voltage stability. For transient voltage stability, the dynamic characteristics of loads such as induction loads are critical. Loads of the AC systems supply or consume two sorts of power. Represented as active and reactive powers. List of loads at each bus are given in Appendix x.

1.4.6 Buses

In the north of Iraq, power system buses are classified into three types.

1. Swing or slack bus: One bus in DGPP is taken as the reference where the voltage magnitude and phase angle are specified [5, 6, 8].
2. P-Q or load buses: the bus voltage magnitude and phase angle of the voltage are unknown. Active and reactive power buses are known. In this thesis has 101 load buses [5, 6].
3. Voltage controlled buses or regulated buses: north of Iraq’s power system consists are 32 P-V buses. The true power and magnitude of voltage are specified. The phase angles of the voltages and the reactive power are to be computed. At these buses, the levels on the value of the reactive are also known [5, 6].

Figure 1.7 Three main component of power system.

1.5 Literature Review

T. Pirzadeh M. SajediHir, Y. Hoseinpoor, P. MosadeghArdabili.(2011). Analysis and Simulation of an STATCOM for Midpoint Voltage Regulation of Transmission Lines. FACTS devices such as SVCs and STATCOMs played an important role in management the reactive power flow to the power network and hence both the transient stability and system voltage fluctuations. They have explained the principle structures of STATCOM and the impact of STATCOM device on midpoint voltage regulation, then compared with that of the customarily static var compensator (SVC) under the fault condition. Effects of two shunts Flexible AC Transmission System devices such as SVCs and STATCOMs on the studied power system is presented. Finally, the simulation results proved that STATCOM is effective in midpoint voltage regulation on a transmission line. SVCs and STATCOMs work on different principles [9].

Ding Lijie, Liu Yang Test and research institute Sichuan electric power Chengdu, China and Miao Yin College of Engineering Electrical department Zhejiang University Hangzhou. (2010). Comparison of high capacity STATCOM and SVC in the real power grid. International Conference on Intelligent Computation Technology and Automation. They have used two modern techniques to management reactive power flow thereby voltage control. Their Simulation results are presented as high ability static var system for SVC or STATCOM is placed on the transmission path of the power system. Firstly, single STATCOM and SVC are limited in voltage comforting after fault occurrence, but STATCOM is little better than SVC. Secondly, SVC is much worse than STATCOM in improving the transient stability and transmission limit. Thirdly, on the damping low-frequency oscillation, SVC is much worse than STATCOM as STATCOM and SVC have the same ability and execute similarly with SVC as the two have the same controllable ability. Lastly, the results also indicated that dynamical response speed effects the control result from little though SVC responses much slower than STATCOM [10].

Darn H. Amin Mohammed. (2013). voltage stability analyzing of KR 132kV Network (30 buses) has been studied using PSAT toolbox. It has been declared that voltage stability it could not be secured with increasing of loads or outage of lines, which may cause voltage collapse in an area or entire network. To dedicate the sensitive or weak line (s) FVSI indices been chosen. Three scenarios have been picked to simulate the network and find critical lines in the system that could cause system unstable [11].

Soumesh Chatterjee, et.al. (2013). they make comparisons between DG, SVC and fixed capacitors in a radial test distribution systems. It is shown that using DG in this kind of network will improve voltage profile and increase a reliability of the system better than SVC and fixed capacitors [12].

This paper prepared by Mehrdad Ahmadi Kamarposhti, Mostafa Alinezhad, Hamid Lesani, Nemat Talebi. (2008). IEEE Electrical Power & Energy Conference. Comparison four techniques SVC, STATCOM, TCSC, and UPFC for Static Voltage Stability Evaluated by Continuation Power Flow Method. Depending their idea, one of the major causes of voltage instability is the reactive power limit of the system. Management or Controlling reactive power flow handling capacity via Flexible AC Transmission System (FACTS) controllers is a remedy for prevention of voltage unsteady and hence voltage collapse. They have elucidated the effects of four FACTS techniques such as SVC, STATCOM, TCSC, and UPFC, on voltage controlling. Results presented that UPFC provided higher voltage stability margin than TCSC, SVC, and STATCOM. Depending the test results requires reactive power the largest at the weakest bus, which is located at the distribution level. SVC and STATCOM give better voltage profiles compared with TCSC since the capacity of STATCOM and SVC is higher at the collapse point than that of TCSC. It was found that this FACTS inspector significantly enhances the voltage profile and thus the load capability margin of power systems [13].

S Bagchi, Assistant Professor, Dept. of Electrical Eng. BCET Durgapur, RBhaduri Associate Professor Dept. of Electrical Eng. BCET Durgapur, P N DDS Associate Professor Dept. of Electrical Eng. NIT Agartala and S Banerjee Professor Dept. of Electrical Eng. NIT Durgapur. (2015). Examination of power transfer capability of a long transmission line using FACTS Devices. They are using three techniques such as SVC, STATCOM, and UPFC to the improvement of power transferred capability. That power grids consisted of two equivalent sources of 500KV 3000MVA each, with 700 km long transmission line. In this International Conference, paper presented the power flow control and increased the power transfer capability [14].

PrityBisen and AmitShrivastava, Department of Electrical & Electronics Engineering, Oriental College of Technology, Bhopal, (MP). (07 October 2013). They have investigated comparison of SVC and STATCOM performance of the two area multi-machine power system for the transient stability improvement. They are understood that above devices capable of controlling the reactive and active power flow in a transmission lines by controlling appropriate parameters. Presented the effects of STATCOM and SVC on transient stability performance of the power system. Simulation results demonstrate the effectiveness and robustness of the proposed SVC and STATCOM on transient stability improvement of the system. The STATCOM gave superior performance than SVC for power measurement, bus voltages and rotor angle and terminal voltages of the multi-machine system. The best performance has been obtained by introducing FACTS devices such as SVC and STATCOM, which compensated reactive power; it's concluded that by introducing FACTS device system performance, voltage stability and transmission capability improves considerably [15].

This paper that prepared by ZHOU Jianguo1, SUN Qiuye1, ZHANG Huaguang1, ZHAO Yan1, In Chinese control conference July25-27,2012, Hera, China, Load Balancing and Reactive Power Compensation based on Capacitor Banks Shunt Compensation in Low Voltage Distribution Networks. Power quality problems mainly resulted from the unbalanced load, this problem transverse repayment method of containing only capacitor banks that have an unequal capacity of capacitors is proposed by above persons for the low-voltage three-phase four-wire distribution networks. They are selected method allows almost total or total symmetry of active power and a complete compensation of reactive power of the unbalanced load. The structures of the compensatory conducted to some clear advantages such as small volume, low costs, simplified structures, high precision of compensation and easy control. Presented job sustains a new method applied to reactive power compensation and load symmetry by using the model containing only. Capacitor banks that are controlled by robust grouping compound switches. This method can be used for the low voltage three-phase four-wire distribution networks. The analysis and putting into effect of the new method and the prototype compensatory developed in the laboratory have been carried out. The good performance has been presented for load balancing, reactive power compensation, current neutral elimination and harmonic elimination in their experiment [16].

Farhad K. Khadr (M. Sc. Thesis, Czech Technical University in Prague, (2013)). Voltage stability of KR network have been studied for summer 2013 using two type of program simulators (BIZON and PSAT). Series and Parallel techniques have been inspected to improve voltage stability; some buses are designated to locate both parallel and series FACTS to improve stability in the system. To find optimal location CPF and QV curve techniques been used [17].

Nang Sabai, Hnin Nandar Maung, and Thida Win. In World Academy of Science, Engineering and Technology 42 2008. Dynamic Performance and Voltage Control of Power Transmission System Using SVC. This paper presented how SVC has successfully using practically to control transmission systems dynamic performance for system disturbance and effectively regulate system voltage. The main major reason for installing an SVC is to increase system load ability and improved dynamic voltage control There is the mainly accomplishes work to construct an effective for SVC. Firstly, to design a controller for SVC techniques on transmission lines, a Single Machine Infinite Bus (SMIB) system is modeled. A stated space mathematical model is analyzed which considers both reactive current of the SVC and electromechanical oscillations at the installation site. The SVC is more effectively enhance the transient stability and increase transmission ability [18].

This paper is prepared by Rajalakshmy, Jay Paul. International Journal of Modern Engineering Research (IJMER). In Aug. 2014. Improve Voltage Stability by Reactive Power Rescheduling Incorporating PSO Algorithm. They are understood that reactive power rescheduling is done to stay the voltage stable. Due to system disturbances the active as well as reactive power flow changes. Generators being constantly connected to the system reactive power rescheduling of generators can be effectively done. Therefore, it is chosen as the suitable method for voltage control. The reactive power control voltage management is contrived from the generator’s point of view to reduce generator reactive power loss. To reduce the reactive losses' optimization procedure is used. Reactive power rescheduling was applied in their research paper; Reactive power rescheduling was discovered that by using the Particle Swarm Optimization technique the reactive losses can be reduced along with the voltage stability attainment. The use of this technique investigated to give an added advantage of minimizing of active power losses [19].

KHALIQ AHMED, VEERESH. In Proceedings of Second IRF International Conference, 30th November-2014, Mysore, India, ISBN: 978-93-84209-69-8. Analysis and comparatively, of reactive power compensation between SVC and STATCOM compensation techniques using MATLAB/SIMULINK. In the power system, during the performance of a system is investigated then the investigation is mainly governed by their stability with the different Faulty conditions that include their Transient Stability, steady state and recovering of the system after being subjected to such type of condition. Answered which type of compensation controllers gives the better stability regarding reactive power compensation. Cleared operating characteristics of SVC and STATCOM is discussed. Though the fundamental law of operation of both the shunt Flexible AC Transmission system devices is different, however, both of them is used to improve the behavior of power system under the Transient condition. STATCOM is a VSC-based FACTS or generating the Reactive Power Independent of System Voltage; on the other hand, SVC is Thyristor-based FACTS Device and works on the principle of Variable Impedance using controlling the firing angle of the high-speed semiconductor switch. The time response of the SVC is slower than compared to STATCOM. STATCOM controller has the attributes of Superior dynamic response and fast fault recovery as compared to that of conventional SVC [20].

Arthit Sode-Yome and N. Mithulananthan. In International Journal of Electrical Engineering Education 41/2. Comparison of shunt capacitor, STATCOM, and SVC in static voltage stability margin enhancement. They have presented compression between three shunt techniques, STATCOM, capacitor and SVC in static voltage stability improvement. Particularly sizing and installation location is important issues, for exclusive load margin improvements are addressed. A comparison of the SVC, STATCOM, and shunt capacitor used for static voltage stability margin enhancement is presented. The importance of selecting an adequate size STATCOM and SVC is also discussed; this is an important issue as far as voltage stability is concerned, as these controllers suffer voltage control problems at the limits. Shunt capacitor, SVC, and STATCOM increase the static voltage stability margin and power transfer ability. However, STATCOM and SVC provide better behavior regarding loss reduction and voltage profile. More losses with a shunt capacitor under lightly loaded conditions are due to the poor voltage profile. Can be implemented to solve the voltage control problem at the shunt capacitor bus by a remote voltage control scheme. Overall, STATCOMs and SVCs behave better than a simple shunt capacitor; however, these controllers are more expensive when compared to the shunt capacitor. A complete cost–benefit analysis has to be carried out to justify the economic viability of the STATCOM and SVC [21].

Anwar S. Siddiqui and Tanmoy Deb. In International Journal of Computer Applications (0975 – 8887) Volume 88 – No.14, February 2014. Their topic Voltage Stability Improvement using STATCOM and SVC. Reactive power limit of the system depends on voltage Stability in the power system. Shunt Facts devices improved the imaginary power flow in the TL, thereby improving stability of voltage. Investigated effect of SVC and STATCOM on static voltage stability. They are utilized IEEE- 14 bus system to demonstrate the ability of SVC and STATCOM in improving the voltage stability margin. Above techniques controllers help to increase the load ability margin of the power network. A comparative analysis of SVC and STATCOM in static voltage stability enhancement is presented. Both, STATCOM and SVC improved static voltage of the buses. STATCOM controller provides higher reactive power support with a faster response time but is expensive. On the other hand, SVC is a cheaper substitute for relatively longer response time. But being capacitor based, the reactive power supported by bus falls significantly at the time of the fault. Hence, STATCOM provides a robust option. Hence, the comparison indicates STATCOM controller is suitable for static as well as dynamic voltage restoration [22].

Chetan E. Morkhade, et.al, in 2013. Main reasons for instability and low voltages at transmissions and substations have been declared, and how FACTS helped to improve the voltages and predicted blackout of the system. FACTS controllers have been classified into four main parts and each part for several types. STATCOM have been picked up in this study to improve voltages [23].

S. S. Chandrakanth, A. Ramulu in Aug. in 2013 International Journal of Modern Engineering Research (IJMER). Optimal Location of STATCOM for Power Flow Control. Voltage and Power flow control in a long transmission line play a vital role in electrical power system. For the control of voltage and power flow using Shunt connected STATCOM. STATCOM is used in various locations such as sending end, middle and receiving the end of the transmission line. The firing pulses of the controller circuit generated by the PWM control. Simulation modeling of the system is carried out using MATLAB/SIMULINK. Based on a VSC, shunt device regulated system voltage by absorbing or generating reactive power. He is dealing with a cascaded multilevel converter model. The objective is to power system voltage control and defines the reactive power generated at different locations (at sending end, middle, receiving end) to the transmission line using STATCOM. SVC and STATCOM are connected at the different locations such as sending end, middle and receiving the end of the transmission line. Based on a VSC, the STATCOM regulates system voltage by absorbing or generating reactive power. The simulation results are obtained with and without compensation and at the middle of the transmission line the reactive power generated by STATCOM is better when compared with SVC. So, optimum location of STATCOM is when connected at the middle of the very long transmission line [24].

Dr. Ibrahim Hamarash Modeling and Simulation of Planned Kurdistan Regional Power System/Iraq, in 2007, Department of Computer and Electrical Systems Engineering, PO Box 35, Monash University, Clayton Victoria 3800, Australia. He has presented an evaluation of the planned Kurdistan Regional Power System/Iraq (KRPS) to maintain stability under small and large disturbances during normal and abnormal operating conditions. To obtain this objective, a complete mathematical model in the form of block diagram, based on manufacturers and IEEE standards and benchmarks data has been derived from the system using MATLAB/SIMULINK/ SIMPOWERSYSTEMS tools. The model represents accurately all the power system components included in physical phenomena of dynamic system oscillations. The model contains 53 transmission lines, 35 nodes and 6 generation stations. The system is simulated under different configurations, and the dynamic behavior associated with each configuration is studied [25].

S. Ravi Kumar, et.al, in 2013. Voltage profile and power quality of transmission system for different loads have been studied with and without using SVC type of FACTS. Authors model six different static load modules and illustrate their effects of on optimal location of SVC. Finally, they conclude SVC will perform better by choosing it to the nearest load side, which will give better voltage regulation, power factor and best reduction of losses [26].

1.6 Arrangement of the thesis

Chapter one: gives a summary information on the north of Iraq main network until 2015, explain how the system is distressing from low voltages. More detail information of main components of the network is given. A literature review of previous paper and studies and researches that done previously related to my thesis. Problem statement and contribution with the main objective of this thesis.

Chapter two: Explain power system stability and power system insecurity in general.

Chapter three: Techniques for reactive power and voltage control and more information about flexible AC transmission system (FACTS) controllers.

Chapter four: simulates the north of Iraq's power system network and compare results with the results of other techniques.

Chapter five: conclusion simulation results and future work.

CHAPTER 2

POWER SYSTEM STABILITY AND POWER SYSTEM INSECURITY

Chapter two is a general introduction to presenting a power system stability and power system insecurity. Power system stability consisted of voltage stability, frequency stability, and rotor angle stability [27]. In this thesis especially explained voltage stability that has the strong relationship with reactive power. In the power system, the main important point transfers maximum active power to the customer side with constant frequency and voltage level.

2.1 Power System Stability and Power System Security

Power system stability is the "ability of an electric power system, for a given initial activating condition, to the recovery of possession a state of operating equilibrium after being an exposition to a disturbance, with most system variables bounded so that pragmatically the entire system remains intact". We understand a qualified absence of danger of disruption of continued system operation, by power system security, system security may be defined of view a control point of view as the probability of the system's operating point residual in a viable state space, given the probabilities of changes in the system (contingencies) and its surroundings (weather, customer demands, disturbances, etc.). System security is the ability of a power system in normal operation to undergo a likely disturbance without entering an emergency or a restorative state. It is used to control the power system in the normal state.[28]

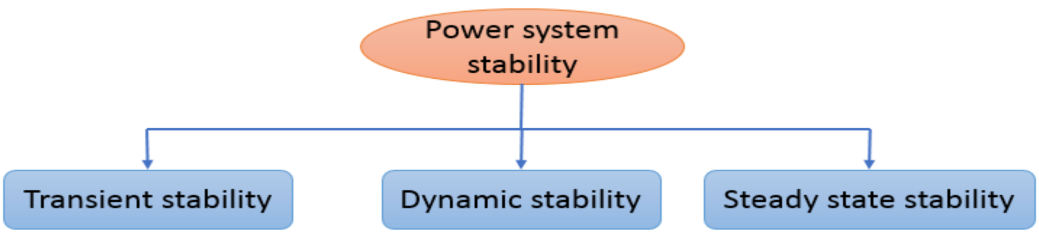


Figure 2.1 Classification of stability

In general the main importance of power system stability is kept generators in synchronize, if their relative motion beings to change too much, uncontrollable oscillations may appear in the grid causing damage generators and equipment, therefore, to perceivable this condition and trip generators before the damage always occurs relays are used. Although trapping prevents the injury, it results in under-frequency, and possibly load interruption, and in the worst case, cascading outages and blackout. Types of stability studies are:

2.1.1 Transient Stability

This interest with sudden and large changes in the network conditions. Transient stability refers to the phenomena of loss of synchronizing that may occur between the different generators of a system in the aftermath of a large disturbance. Transient stability is the capability of the network to maintain synchronize when it is suddenly subjected to severe transient physical disturbance, such as loss of transmission lines or generators, a fault, sudden or sustained load changes and severe shock to the system due to the switching operation. Because of the severity and suddenness of the disturbance, the analysis of fleeting stability is focused on the first few seconds, or even the first few cycles, following the fault occurrence or switching operation [4]. First swing analysis sometimes called transient stability studies, during the period following severe disturbance, the generator undergoes its first transient overshoot or swing. When the generator can get through it without losing synchronize, it is said to be transient stable. But, if the generator loses its synchronize and cannot get the first swing, it is said to be transient unstable [8].

2.1.2 Dynamic Stability

Dynamic stability is the ability of a power system to maintain synchronize after sudden and small disturbance. The power system can be described by linear differential equations, and can be stabilized by a linear and continuous supplementary stability control [1, 28]. Dynamic stability is the extension of steady-state stability where the dynamics of synchronous machines and automatic voltage regulator are included. It is concerned with small disturbances lasting for a long time as the change in load, changes in turbine speed. And therefore the nonlinearity is neglected in dynamic stability studies, i.e. the system is assumed linear [37].

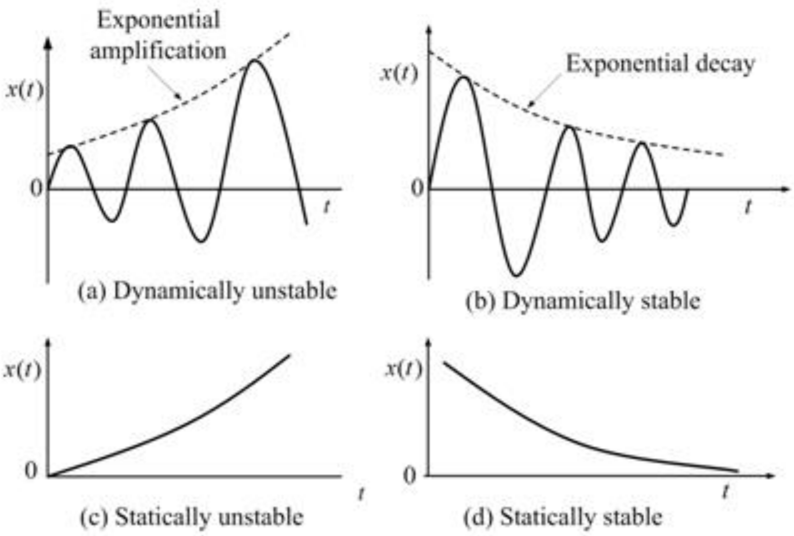


Figure 2.2 dynamically and statically of stability and unstable responses

[http://code7700.com/stability.html]

2.1.3 Steady State Stability

Steady state stability is the ability of the electrical power network to sustain synchronize after weakly and slow disturbance or weakly - signal stability is the capability of the PS to return to a regular operating state following a small disturbance. The error between input and output almost equal to zero. Inspections involving this stability concept involve the dissection of the winterized state space equations that define the power dynamic. Steady-state stability studies are less extensive in scope than transient stability studies and often involve a single machine operating into just a few machines or an infinite bus undergoing one or more small disturbance [6,37].

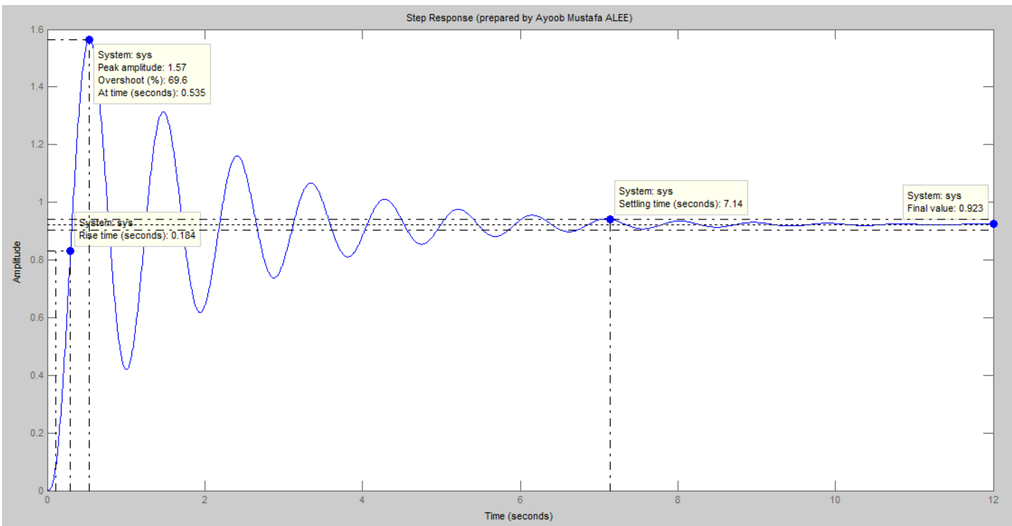


Figure 2.3 Transient and steady-state actual time response stability.

Power System Stability divided into [27]

- Frequency stability.
  - Long term frequency stability.
  - Short expression frequency stability.
- Rotor angle stability:
  - Transient stability.
  - Small disordered or disturbance angle stability.
- Voltage stability.
  - Small disordered or disturbance voltage stability.
  - Large disordered or disturbance voltage stability.

Power System Security divided into [28]

- Dynamic security.
- Static security.

- Reasons of system security are variations of system bus voltage, imbalance between generated power & load demand, variations of system frequency and overloading.
- In this study, we are discussion only about voltage stability in the power system. And clearly understand this equation, why the power system voltage goes to instability or insecurity? And what are effects above problem over power system? Finally, how we can compensate this problem?

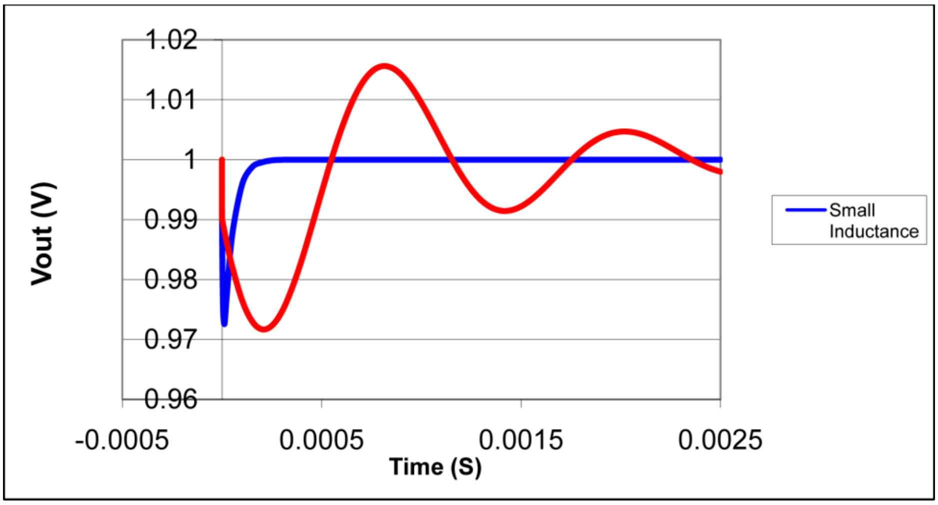


Figure 2.4 Small inductance load and large inductance load

[http://m.eet.com/media/1123411/c0994-figure2.gif]

2.2 Voltage

Voltage is the charge rate of doing the job. One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other [40]. To guarantee the electricity supply for the customers, some certain institutions are required, one of them is voltage. In the north of Iraq, electrical power system voltage regularity problem has become a great interest in power systems, especially for a system with heavier loading conditions at the summer and winter season and without adequate transmission or generation enhancements. Maintaining the balance between generation and consumption. So as to guarantee voltage stability at all buses in the north of Iraq's electrical power system, the transmission line impedance must be quantified. Transmission lines and underground cables are made out either of copper and aluminum. Above materials present a small resistance to the flow of electrical current when considering the long distances over ed by T.L. A most common method of alternating current power transmission and distribution are three phase systems, carry tree AC by three circuit conductors that reach their instantaneous peak values at different times. Charging crates around the single-phase conductors by the magnetic field when carried the current. The magnetic flux changes corresponding the current changes. As a result of this phenomenon a voltage is generated in the conductor itself and so on in the conductors around it.

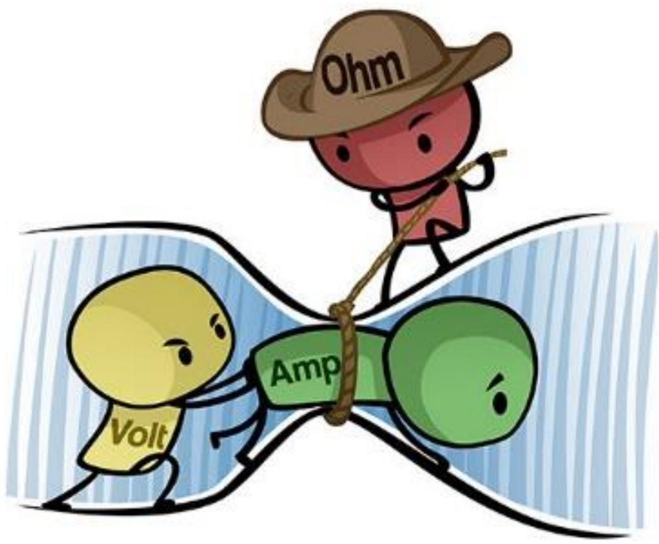


Figure 2.5 Process job between volt, amp, and ohm

[http://www.build-electronic-circuits.com/electronics-for-beginners/]

2.2.1 Voltage Stability

Voltage stability is the ability of a power system to maintain steady, acceptable voltages at all buses in the system under regular operating conditions and after being subjected to a disturbance [8, 27]. Voltage stability can be achieved by sufficient generation and transmission of energy. Transmission and Generation units have definite capacities that are peculiar to them. These limits should not be exceeded in a healthy power system. Voltage stability issue problem arises when the system is heavily loaded that causes going beyond limitations of the power system. Power network enters unhealthy of voltage when transient disturbance and sudden load change or increase. Demand for reactive power is the main factor causing instability. To power operation system under an unfailing condition, a power system has to be designed to withstand a large number of different physical disturbances. This is achieved by designing and operating the power system such that the most probable contingencies will not cause any loss of load, i.e. except at the direct connection to the equipment affected by the fault. It is especially important for the power system to be able to cope with the most severe contingencies without risking an uncontrolled spread of power interruptions (blackouts). TSOs have a set of technical requirements which must be fulfilled throughout the entire power system. They apply from generation, via the transmission and distribution grids all the way to the connected loads (customers). One example of these requirements is limited on voltage level that applies to the terminals of all equipment in the system. The voltages have to be kept within an "acceptable limit" to protect both utility and customer equipment [8, 27].

Loads connected to the system will vary over time. Therefore, the reactive power demand of the system will also vary. This will again lead to a variation of the voltage level of reactive power and voltage are closely coupled. Faults, disconnections, and other contingencies also affect the demand for reactive power and voltage level in the system. It is crucial to keep a close eye on how the voltage level is varying throughout the power system and to make sure it is kept within the required limits. The goal is to have a power system that is "voltage stable". A power system would thus be characterized as unstable if a disturbance led to an uncontrollable drop in voltage. This unstable event is termed as a voltage collapse or voltage instability. Increase the demand for reactive power is the main cause of instability in the power system. Hence, problems with voltage instability most often occur in heavily stressed power systems [5]. Aim of chapter two is to the concept of voltage stability in a power system. This is done to give an insight into how the voltage stability margin of a power system can be extended. Voltage stability classified into two categories

- ✓ Large disordered or disturbance Voltage stability.
- ✓ Small disordered or disturbance Voltage stability.

- ❖ Voltage security may be classified into two main problems [28]
  - ✓ Low voltage: voltage level is outside of the predefined range. It does not necessarily imply voltage instability; no low voltage does not necessarily imply voltage stability.
  - ✓ Voltage instability: an uncontrolled voltage decline. It does necessarily imply low voltage.

2.2.2 Voltage Instability

Voltage changeability results in progressive fall or rise of voltages of some buses. Occurs under heavy loading conditions or any physical distraction [5]. This problem causes extremely low voltages below acceptable limits. What the voltage at the P-Q bus falls despite power is expected to increase. Normally, a power system has connected demand loads that are lesser than the maximum transfer power ability of the generation plant and transmission network. However, desolation losses of lines may significantly increase transmission reactant. Generators may also hit their reactive capability limits culminate in an inability to sustain voltage at key points in the power system network. A stronger transmission lines and adequate reactive power reserves, to maintain voltages at key points in the network, are required to avoid voltage unsteady [6]. some types of voltage disturbances in the transmission systems are demonstrate:

2.2.2.1 Voltage Swell and Surge

Voltage swell and surge are a voltage rise that endangers of electric equipment's insulation. Swells, originally referred to as surges, except that the voltage exceeded a user-defined high limit. Voltage Swell increase to between 1.1 Pu and 1.8 Pu in RMS at the power frequency with the duration of more than one cycle and typically less than a few seconds [4]. At many resources, fixed capacitors are used to reduce cost, and they are those that are permanently connected to the PQ bus and are not switched off and on as the load changes. The shutdown of heavily loaded circuits causes that the voltage is increased due to the capacitor being sized for the higher load. The limit on steady state voltage is taken to be 1.1 pu of the rated voltage. If the reactive power doesn't absorb by any techniques, transformers will saturate and overheat, by voltage is a rise, mis-operation of equipment may occur, and equipment life will be reduced [5]. Start/stop of heavy loads, dimensioned power sources, and badly regulated transformers are causes the prevailing bus voltage occurs to be high, due to conditions on the distribution system feeding the facility, the voltage elevation would be added to this already higher voltage. And so, system voltage should be checked when considering voltage rise.

2.2.2.2 Voltage Sag or Voltage Dip

Sag or dip voltage is a decrease in power system voltage. The voltage dip or Sag magnitude is ranged from 10% to 90% of Nominal voltage, and with a duration of half a cycle to 1 min. In a three-phase system, a voltage dip is by nature a three-phase phenomenon that affects both the phase-to-grounded phase-to-phase voltages. Caused by the single line to ground fault, switching on heavy load and starting of large induction loads, such as motors [39].

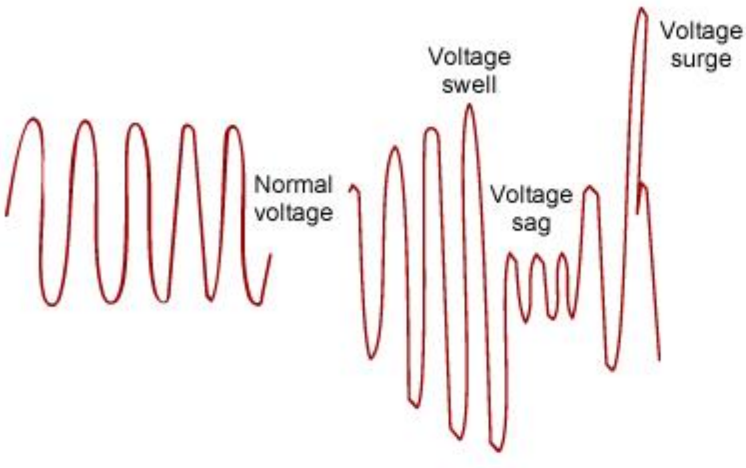


Figure 2.6 Voltage sag (dip) and swell (surge)

[http://www.build.com.au/voltage-supply-fluctuations]

2.2.2.3 Voltage Flicker and Fluctuation

Voltage flicker is a visible phenomenon change in brightness light intensity fluctuation or change in the steady-state voltage below or above below the designated input range for a piece of equipment. Fluctuations include both sags and swells, oscillation of voltage value. Caused by large rapid industrial load changes such as electric arc furnaces, used for melting. Or large equipment start-up/ shutdown, the sudden change in load, pumps operate periodically and rolling mills in a weak power distribution system. Has been a major concern for both customers and power companies in the area of power quality. This flicker is objectionable only when the magnitude and frequency of appearance of the voltage drop exceed certain thresholds. If the frequency and the magnitude of the voltage drop of occurrence lie below the threshold of sense, people do not notice any flicker. Large industrial loads, i.e., for example, scrap with an energy of electric, and cause voltage distortion like voltage fluctuation and harmonics in the AC system feeding. A building of new approaches to power system operation and control are required for overload relief and efficient and reliable operation. Encouraging dynamic disturbances such as transmission lines switching, loss of generation, load rejection and short-circuits, needs the reactive power control to be fast enough to maintain the desired voltage levels and the system stability. Voltage fluctuation can be reduced by using a synchronizing relay (transformers, compensation stages), switch-on damping resistors (short-term), and thyristor switched capacitor batteries in a high-voltage network, flutter compensators based on thyristor modules or IGBT/IGCT converters.

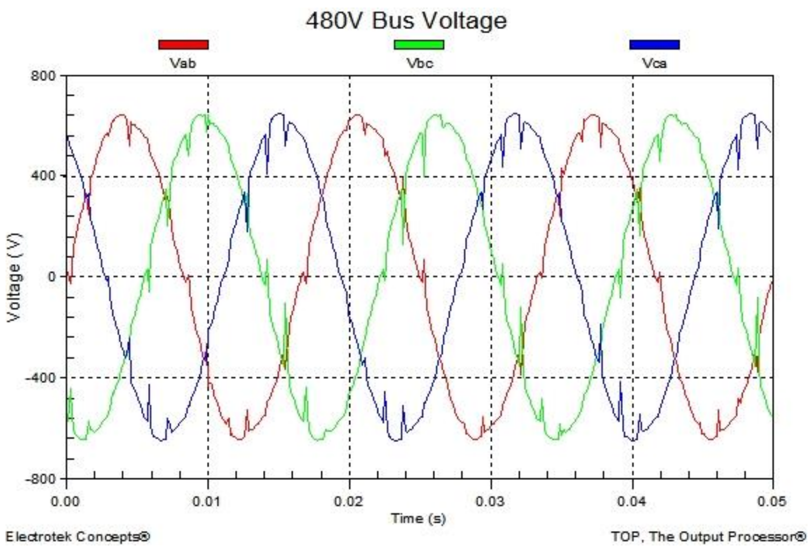


Figure 2.7 Voltage flicker phenomenon

[http://www.edn.com/electronics-blogs/the-signal/4408242/1-f-Noise-the-flickering-candle-]

2.2.2.4 Voltage Collapse

Voltage collapse is the critical point of voltage stability. The power system undergoes voltage collapse if the post-disturbance equilibrium voltages near customers are below acceptable limits. It is may be total (blackout) or partial. The obscurity of voltage stability leads to voltage instability and results in the progressive decrease of voltages. Thus, abnormal levels of voltage in steady state may be the result of voltage instability that is a dynamic phenomenon. The voltage collapse and instability may occur in a time frame of a fraction of a second. In this case, the term 'transient stability of voltage ' is the power system that are heavily loaded, faulted and having a shortage of reactive power are the main reason for voltage collapse [30].

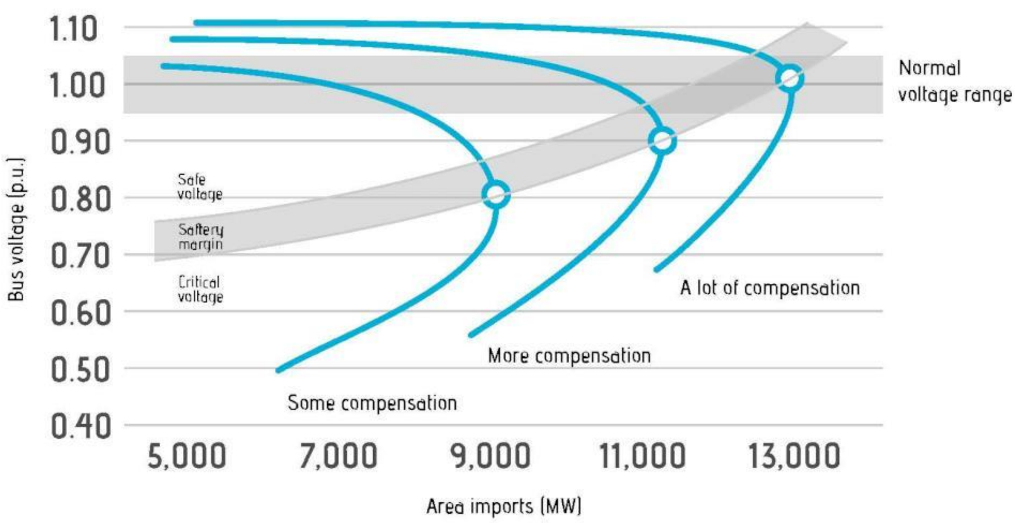


Figure 2.8 Voltage control and voltage collapse

[http://www.eeweb.com/blog/nicholas_abisamra]

2.2.2.5 Voltage Spikes and Transients

Voltage spikes and transients are very fast and short duration electrical passing in voltage and undesirable voltages that appear on the power supply line. Spikes and transients that presented in the figure below are high over-voltage disturbances that last for a very short time.

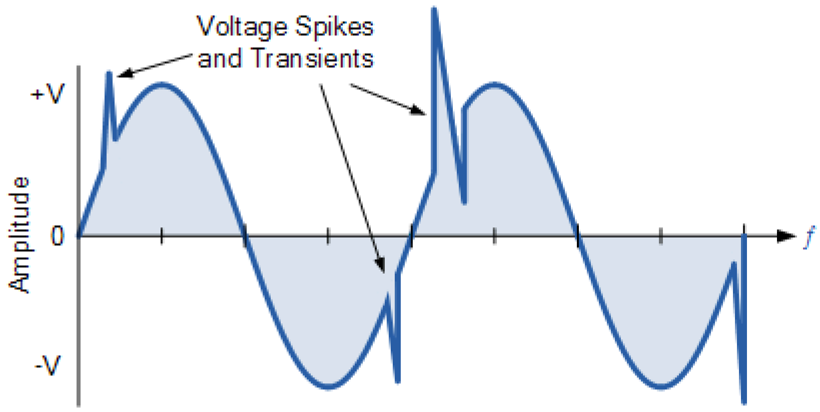


Figure 2.9 Voltage spikes and transients

[http://www.electronics-tutorials.ws/resistor/varistor.html]

2.2.2.6 Voltage Unbalance or Imbalance

Voltage unbalance or imbalance is an aberration from the average of the three phase voltage magnitude. Or the phase angle difference between them are not equal. Single-phase and two-phase electrical equipment can cause unacceptable voltage, unbalance resulting in increased losses, cutting phase, reduced grid capacity, voltage imbalance is caused by different impedances in the electrical distribution system and/or unbalanced loads on distribution lines [43]. We offer customer designed compensation equipment for load-balancing. Our customers by this reduce the voltage imbalance and resulting excessive losses.

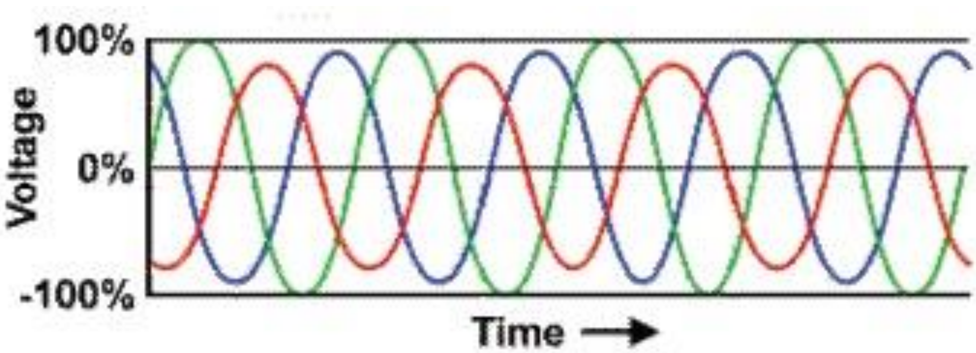


Figure 2.10 Voltage unbalance or imbalance

[http://www.powerqualityworld.com/2011/06/voltage-unbalance-power-quality-basics.html]

2.2.2.7 Interruption Voltage

Instantaneous state, very short deep voltage drop interruptions cause a complete loss of voltage. Or it is 100% reduction in amplitude. Sustained interruptions of longer than 1 minute are due to permanent faults. Voltage Interruption is one type of disturbance power quality problem.

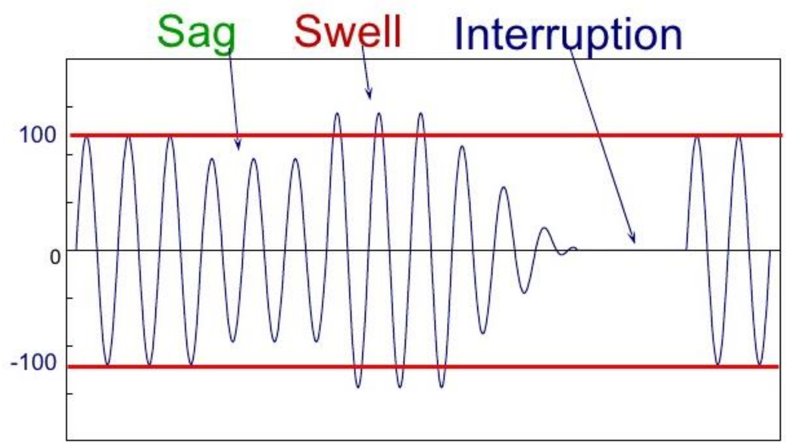


Figure 2.11 Sag, swell, and interruption voltage

[http://www.tequipment.net/fluke/power-measurement/]

2.3 Voltage drop

To receiving the acceptable voltage level by consumers, we have to consider the voltage drop (Vd) in each line of the power system. All the electrical lines have a specific impedance that causes a difference between the sending and receiving end voltage. In a 3-phase line with a positive sequence voltage, we have impedance in the line Z [34]

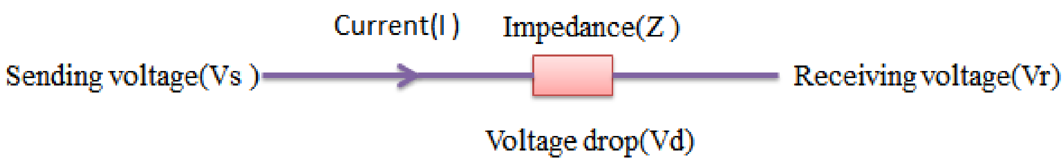


Figure 2.12 Single transmission line

[https://static.tiendy.com/shops/opendaq/uploads/rc_schema.png]

Depending Kirchhoff's voltage law we can compute voltage drop over transmission line:

$$Vs = I*Z + Vr \quad \text{or} \quad Vs = Vd + Vr \tag{2.1}$$

Where:

Vs sending voltage

I current absorbed by load

Z impedance of the line $Z = R + JX$ (2.2)

R Resistance of the line

X Reactance of the line

Vr receiving voltage

Vd Voltage drop

Single phase voltage drop over lines are

$$Vd \approx Ip*R + Iq*X \quad (2.3)$$

Where:

Ip represents the resistive component of the current and Iq the reactive component [4, 34].

If Vpu = 0.9 and I=P/V, I=1/0.9 I=1.11pu, P lose =I*I*P, 1.11*1.11* =1.23pu
When %10 drop in peak voltage produces a %11 increase in current and %23 increase in active losses.

2.4 Power

Power is a measure of energy per unit time [6]. Power, therefore, gives the rate of energy consumption or production [1, 36]. The units for power measurement are watts (W) [9]. For example, the watt rating of an appliance gives the rate at which it uses energy[26]. The complete amount of energy consumed by this appliance is the wattage multiplied by the amount of time during which it was used; this energy can be verbalized in units of watt-hours or, more commonly, kilowatt/hours [9]. The power wasted by an electric element whether an appliance or simply a wire is given by the product of its resistance and the square of the current through it:P=I^2 R The term "dissipated" indicates that the electric energy is being converted to warm. This heat may be part of the appliance's intended function (as in any electric heating device), or it may be inspection a loss as in the resistive warming of transmission lines the physical operation is the same. Another, a more public way of calculating power is as the product of current and voltage: P=I*V. For a resistive element, we can apply Ohm's law (P=I*V) to see that the formulation P=I^2 R and P=I*V amount to the same thing.

2.4.1 Apparent Power (S)

It is a complex power. An apparent power is a power that is supplied to the circuit that's total power (S) is the gathering of active and reactive power. Apparent power is measured in VA, k VA, MVA.

$$S=P+JQ \quad (2.4)$$

2.4.2 Active Power (P)

True or real power, it is the useful power on the consumer load. That is doing the actual work. It is measured in W, kW, MW & computed as,

$$P = S * \cos \varphi \quad (2.5)$$

2.4.3 Reactive Power (Q)

It is an effect of an AC system.it is wasted and not used to do work for the consumer. Reactive power is used to build up magnetic fields. It is calculated as,

$$Q = S * \sin \varphi \quad (2.6)$$

or $P * \tan \varphi$, & measured in var, kvar, Mvar.

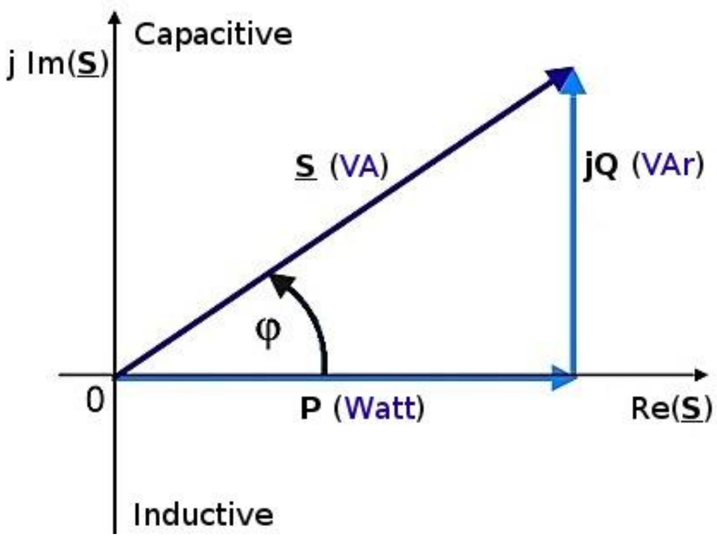


Figure 2.13 Apparent power(S), Active power (P) and Reactive power (Q)

[http://www.wikiwand.com/en/AC_power]

2.4.3.1 Reactive Power Limitations

Reactive power does not transfer very far. Necessary to produce it close to the location where it is needed. A source/supplier closest to the location of the need is in a much better position to grant reactive power versus one that is located far from the location of the need. It is supplied are closely tied to the ability to deliver real or active power.

2.4.3.2 Maintain a System Healthy by Reactive Power Management

Always in practice try to reduce reactive power flow to improve system efficiency. Much capacitance or inductive load make cause some problem. Power systems supply or consume two kind of power, true power, and reactive power. While reactive power upholds the voltage that must be controlled for system credibility, It has a profound effect on the security of power systems because it affects voltages throughout the system. When reactive power supply lower voltage, as voltage drops current must increase to maintain power supplied, at that moment consume more reactive power, and the voltage drops further. Transmission lines go offline when the current increase too much, overloading other lines and potentially causing cascading downfall. When the voltage drops too low, some generators will cut off automatically. Collapse occurs when an increase less generation or in load or transmission facilities causes dropping voltage, if stay voltage reduction, it will cause additional elements to trip, leading a further decreasing in voltage and loss of the load side. The result in these entire progressive and uncontrollable declines in voltage is that the power system unable to supporter the reactive power required supplying the reactive power demands. [35, 36]

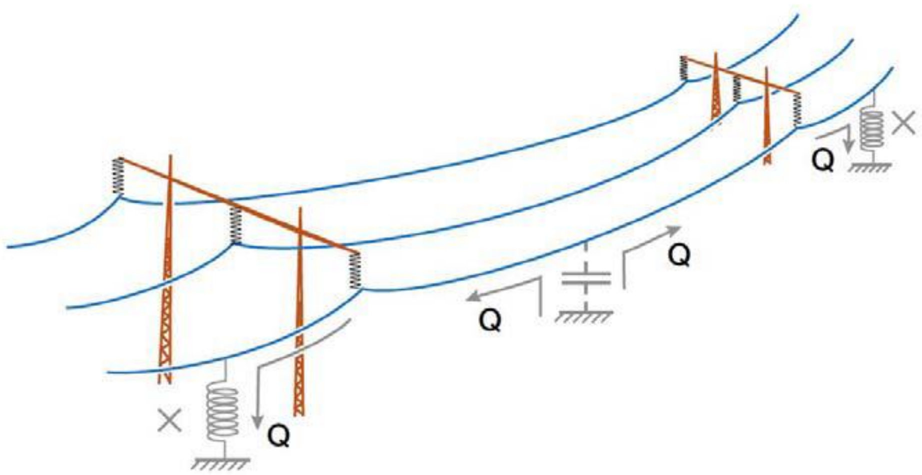


Figure 2.14 Supporter capacitor near inductive load [35]

2.5. Power Factor (cos φ)

Power factor is a measurement of the capability or efficiency in a power system. It is the cosine of the power angle between voltage and current. Power factor depiction the relationship between apparent power (S) and active power (P). Represented as kW/kVA. Active (real) power is the numerator, and apparent power is the denominator. Depending type of load it is besieged between 0 and 1 [4].

- Inductive load consumed reactive power. The current waveform lags the voltage; power factor is lagging.
- Capacities load produced reactive power. The current waveform leads voltage waveform and power factor is leading.
- The Resistive load didn't consume and produced reactive power. Unity power factor.

In this study attempt to obtain nearby unity power factor by reactive power compensation.

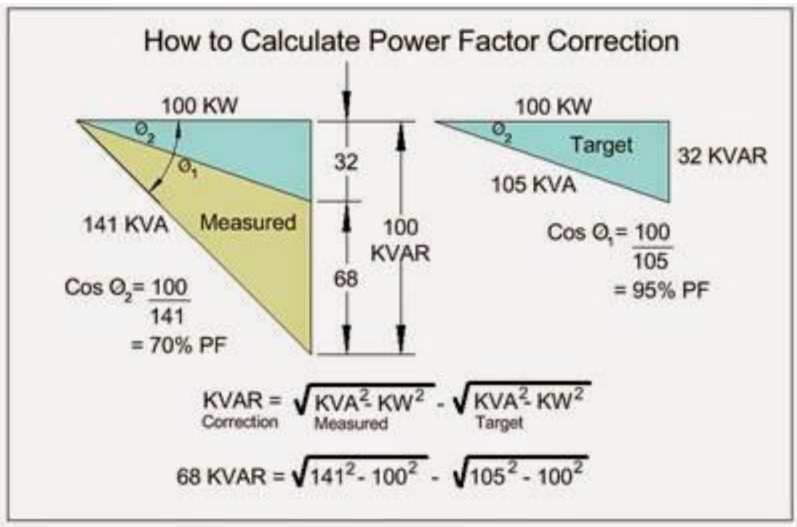


Figure 2.15 Power factor calculation [4]

2.5.1. Causes Low Power Factor in the Electrical Power System

Low power factor is expensive and inefficient. Low P. F also minimize electrical system's distribution capacity by increasing current flow (reactive power flow) and causing voltage drops. Assorted causes, which can be attributed to low power factor, may be listed as follows [4]

- Inductive loads. Especially lightly loaded induction motors, and transformers.
- Fault limiting reactors
- High voltage drop.
- Induction furnaces
- Arc lamps and arc furnaces with reactors.

2.5.2 Power Factor Enhancement

Reactive power flow over transmission lines minimizes, by adding techniques of reactive power control in the electrical power system like FACTS family, capacitor banks, or synchronous motors. That's cause to improve power factor. Power factor can also be improved by transformers and fully loading induction motors and also by using higher rpm machines. Usage transformer's automatic tap changing can also help to maintain better power factor [4].

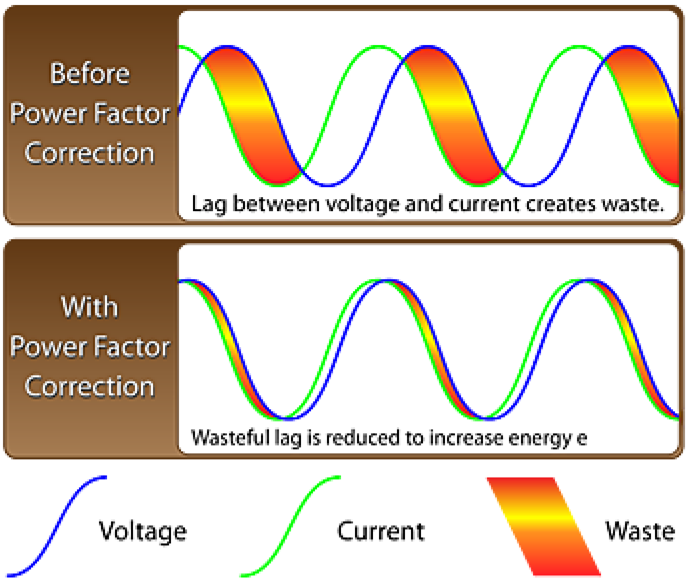
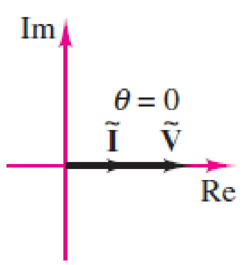
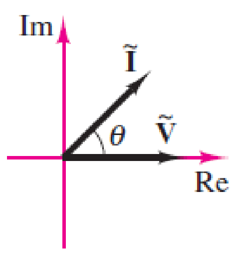
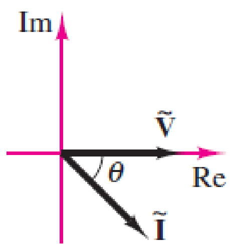
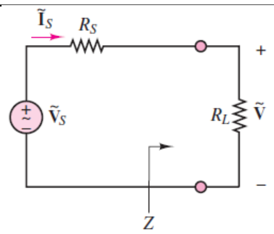
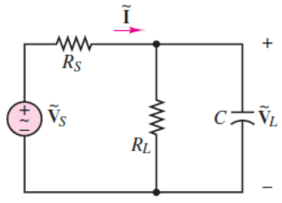
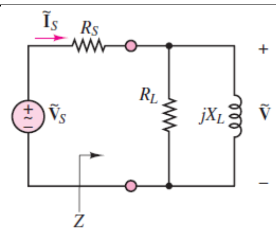


Figure 2.16 Power factor correction [44]

A power factor close to unity signifies an efficient transfer of power from the AC source to the load while a small power factor corresponds to the inefficient use of energy. If the power factor is less than unity, some additional current will be drawn from the source, lowering the efficiency of power transfer from the source to the load. However, it will be shown shortly that it is possible to correct the power factor of a load by adding an appropriate reactive component to the load itself. Since the reactive power Q is related to the reactive part of the load, its sign depends on whether the load reactance is inductive or capacitive. Table 2.1 illustrates the concept and summarizes all the important points so far.

Table 2.1 all the important points of power factor [35]

	Resistive load	Capacitive load	Inductive load
Power factor	Unity	Leading	Lagging
Reactive power	0	Negative	Positive
Explanation	The current is in phase with the voltage.	The current "leads" the voltage.	The current "lags" the voltage.
Phase angle	0	< 0	> 0
Ohm's law	$V_L = I_L Z_L$	$V_L = I_L Z_L$	$V_L = I_L Z_L$
Complex impedance	$Z_L = R_L$	$Z_L = R_L - jX_C$	$Z_L = R_L + X_L$
Complex plane sketch			
figure			

We will explain three case that presented from table 2.1. Unity, leading and lagging power factor to calculate active power transfer from sending end to load [35]

- **Case one when the load consists of only resistance**

$V_S = 100V, R_S = 2\Omega, R_L = 15\Omega,\ Z_L = R_L = 15\Omega$(because only resistance load)

$$V_L = \frac{Z_L}{R_S+Z_L} * V_S \quad (2.7)$$

$$V_L = \frac{15}{2+15} * 100V \Rightarrow V_L = 88.24V$$

$$V_{drop} = 100 - 88.24 = 11.76V$$

$$I_L = \frac{V_L}{Z_L} \quad (2.8)$$

$$\Rightarrow I_L = \frac{88.24}{15} \Rightarrow I_L = 5.88A$$

$$S_L = V_L * I_L = P_L + JQ_L \quad (2.9)$$

$$\Rightarrow S_L = 88.24 * 5.88 \Rightarrow S_L = 518.85W + J0VAR$$

$$I_S = \frac{V_S}{Z_{total}} \quad (2.10)$$

$$\Rightarrow I_S = \frac{100V}{17\Omega} \Rightarrow I_S = 5.88A\ = I_L \text{ because series}$$

$$S_S = V_S * I_S = P_S + Q_S \quad (2.11)$$

$$\Rightarrow S_S = 100 * 5.88 \Rightarrow S_S = 580W + J0VAR$$

$$\text{PERCENTAGE POWER TRANSFER} = \frac{S_L}{S_S} = \frac{518.85}{580} = \mathbf{0.8945} \quad (2.12)$$

$$P_L = V_L * I_L * \cos\theta \Rightarrow P_L = 88.24 * 5.88 * 1 = 518.85W\ \ (\cos 0 = 1) \quad (2.13)$$

$$Q_L = V_L * I_L * \sin\theta \Rightarrow Q_L = 88.24 * 5.88 * 0 = 0VAR\ \ (\sin 0 = 0) \quad (2.14)$$

$$P_{loss} = {I_S}^2 * R_S \Rightarrow P_{loss} = 5.88^2 * 2 \Rightarrow P_{loss} = \mathbf{69.15}W \quad (2.15)$$

$$P_S = P_L + P_{LOSS} \Rightarrow P_S = 518.85W + 69.15W \Rightarrow P_S = 588W \text{ result is correct}$$

$$\text{PERCENTAGE Active POWER TRANSFER} = \frac{P_L}{P_S} = \frac{518.85}{580} = \mathbf{0.8945}\% \quad (2.16)$$

- **Case two when the load consists of a capacitive and resistance**

$V_S = 100V, R_S = 2\Omega, \quad R_L = 15\Omega, \quad C = 470\ \mu F\ (w = 2\pi fc)$

$$Z_L = R_L \parallel \frac{1}{JW_C} \Rightarrow Z_L = \frac{R_L * \frac{1}{JW_C}}{R_L + \frac{1}{JW_C}} \Rightarrow Z_L = \frac{R_L}{JW_C * R_L + 1} \Rightarrow Z_L = 6.17\angle - 65.69\Omega \qquad (2.17)$$

$$V_L = \frac{Z_L}{R_S + Z_L} * V_S \Rightarrow V_L = \frac{6.17\angle - 65.69}{2 + 6.17\angle - 65.69} * 100V \Rightarrow V_L = \frac{6.17\angle - 65.69}{7.22\angle - 51} * 100 \Rightarrow V_L = 85.45\angle - 14.7V$$

$$V_{drop} = 100\angle 0 - 85.45\angle - 14.7 = 17.35 + j21.68V$$

$$I_L = \frac{V_L}{Z_L} \Rightarrow I_L = \frac{85.45\angle - 14.7}{6.17\angle - 65.69} \Rightarrow I_L = 13.85\angle 51A \qquad (2.8)$$

$$S_L = V_L * I^*{}_L = P_L + JQ_L \Rightarrow S_L = 85.45\angle - 14.7 * 13.85\angle - 51 \Rightarrow S_L = 1183.5\angle - 65.7 = 487W - J1078.6VAR$$

$$I_S = \frac{V_S}{Z_{total}} \Rightarrow I_S = \frac{100\angle 0V}{7.22\angle - 51\Omega} \Rightarrow I_S = 13.85\angle 51A \qquad (2.10)$$

$$S_S = V_S * I^*{}_S = P_S + Q_S \Rightarrow S_S = 100\angle 0 * 13.85\angle - 51A \Rightarrow S_S = 1385\angle - 51 \Rightarrow S_S = 871.6W - J1076.3VAR$$

$$\text{PERCENTAGE POWER TRANSFER} = \frac{S_L}{S_S} = \frac{1183.5\angle - 65.7}{1385\angle - 51} = \mathbf{0.8545\angle - 14.7}$$

$$P_L = V_L * I_L * \cos\theta \Rightarrow P_L = 487W \qquad (2.13)$$

$$Q_L = V_L * I_L * \sin\theta \Rightarrow Q_L = -1078.6VAR \qquad (2.14)$$

$$P_{loss} = I_S{}^2 * R_S \Rightarrow P_{loss} = 13.85^2 * 2 \Rightarrow P_{loss} = \mathbf{383.6}W \qquad (2.15)$$

$$\text{PERCENTAGE Active POWER TRANSFER} = \frac{P_L}{P_S} = \frac{487}{871.6} = \mathbf{0.559}\%$$

- **Case three when the load consists of an inductor and resistance**

$V_S = 100V, R_S = 2\Omega, \quad R_L = 15\Omega, \quad JW_C = J6\Omega$

$$Z_L = R_L \parallel JX_L \Rrightarrow Z_L = \frac{15 * J6}{15 + J6} \Rrightarrow Z_L = \frac{90\angle 90}{16.155\angle 21.8} \Rrightarrow Z_L = 5.57\angle 68.2 \quad (2.17)$$

$$V_L = \frac{Z_L}{R_S + Z_L} * V_S \Rrightarrow V_L = \frac{5.57\angle 68.2}{2 + 5.57\angle 68.2} * 100V \Rrightarrow V_L = \frac{5.57\angle 68.2}{6.578\angle 51.8} * 100 \Rrightarrow V_L = 84.67\angle 16.4V$$

$$V_{drop} = 100\angle 0 - 84.67\angle 16.4 = 18.78 - j23.9V$$

$$I_L = \frac{V_L}{Z_L} \Rrightarrow I_L = \frac{84.67\angle 16.4}{5.57\angle 68.2} \Rrightarrow I_L = 15.2\angle -51.8A \quad (2.8)$$

$$S_L = V_L * I^*{}_L = P_L + JQ_L \Rrightarrow S_L = 84.67\angle 16.4 * 15.2\angle 51.8 \Rrightarrow S_L = 1287\angle 68.2 = 478W + J1195VAR$$

$$I_S = \frac{V_S}{Z_{total}} \Rrightarrow I_S = \frac{100\angle 0V}{6.579\angle 51.8\Omega} \Rrightarrow I_S = 15.2\angle -51.8A \quad (2.10)$$

$$S_S = V_S * I^*{}_S = P_S + Q_S \Rrightarrow S_S = 100\angle 0 * 15.2\angle 51.8 \Rrightarrow S_S = 940W + J1194VAR$$

$$\text{PERCENTAGE POWER TRANSFER} = \frac{S_L}{S_S} = \frac{1287\angle 68.2}{1520\angle 51.8} = \mathbf{0.8467\angle 16.4}$$

$$P_L = V_L * I_L * \cos\theta \Rrightarrow P_L = 478W \quad (2.13)$$

$$Q_L = V_L * I_L * \sin\theta \Rrightarrow Q_L = 1195VAR \quad (2.14)$$

$$P_{loss} = {I_S}^2 * R_S \Rrightarrow P_{loss} = 15.2^2 * 2 \Rrightarrow P_{loss} = \mathbf{462}W \quad (2.15)$$

$$\text{PERCENTAGE Active POWER TRANSFER} = \frac{P_L}{P_S} = \frac{478}{940} = \mathbf{0.508}\% \quad (2.16)$$

we can compute the reactive power of the load from knowledge of the real power and of the power factor, to compute the reactance needed for the power factor correction, we observe that we need to contribute a negative reactive power by using capacitor required for power factor correction.in the figure 2.17 we can determine the reactive power when the capacitor is not in the circuit, and compute the required value of capacitance for perfect pf correction [35].

$V_S = 100\angle 0$ V, p.f = 0.8 lagging, real power load = 10^5w

$$|S| = \frac{\text{real power load(P)}}{\cos\theta\,(\text{p.f})} = \frac{10^5\,\text{w}}{0.8} = 125000\ \text{VA} \tag{2.17}$$

$$\text{pf} = \cos\theta \Rightarrow \theta = \cos^{-1} 0.8 \Rightarrow \theta = 36.87 \tag{2.18}$$

$$Q = |S| * \sin(\theta) \Rightarrow Q = 125000 * \sin(36.87) \Rightarrow Q = 75000\ \text{VAR} \tag{2.19}$$

To calculate the reactance needed for the power factor correction, we observe that we need to contribute a negative reactive power equal to −75 kVAR. This requires a negative reactance and, therefore, a capacitor with QC = −75 kVAR. The reactance of such a capacitor is given by [35].

$$X_C = \frac{|V_L|^2}{Q_C} \Rightarrow X_C = \frac{100^2}{-75000} = -0.13334 \tag{2.20}$$

$$C = -\frac{1}{wX_C} \Rightarrow C = -\frac{1}{2*\pi*f*X_C} \Rightarrow C = -\frac{1}{2*3.14*50*(-0.13334)} \tag{2.21}$$

$C = 23{,}884\ \mu\text{F}$

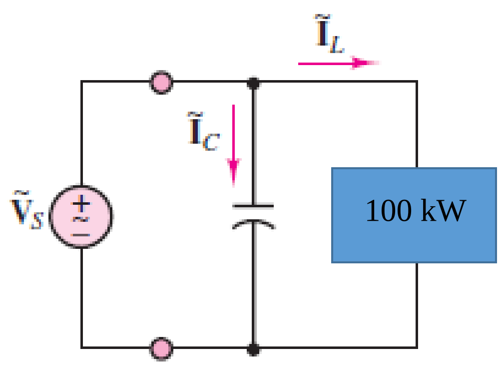


Figure 2.17 Power factor correction [35]

2.6 Power Flow Analysis

2.6.1 Introduction

Power flow studies are of great importance in designing and planning the future expansion of power systems such as adding new generator locations, meeting increased load demand and locating new transmission sites, as well as in determining the best operation of existing networks. Power (load) flow study in the power system is the normal steady state solution of the power system network. This study will determine voltage magnitude |V|, phase angle at various buses in the power system and real power P, reactive power Q flowing in each line. In a power flow solution [30], two out of the four quantities are known, and the remaining two are required to be computed through the solution of the equations. Based on the difference between power flows in the receiving and sending receiving ends, the losses in a particular line can also be calculated. The direct analysis of the circuit is not conceivable, as the load is given regarding complex or complicated powers rather than impedance, generators behave more like power sources than voltage sources. The major information obtained from the power flow study comprises magnitudes and phase angles of load bus voltages, voltage phase angles and reactive powers at generator buses, active and reactive power flow on lines together with power at the slack bus, another variable being specified. In load or power flow analysis, mainly interested in voltages at various buses and power injection into the transmission system. Also, power flow study's is required for many other analyzes such as transient stability and contingency studies. The main objective of a load flow study is to determine the steady state operating condition of the electrical power system. Such information is used to carry out security estimation analysis [26,30], where the nodal voltage magnitudes and active and reactive power flows in transformers and transmission lines are carefully observed to assess whether or not they are within prescribed operating limits [26]. For a power flow problem solving, the system is assumed to be operating under balanced conditions and using a single-phase model [6, 30].

2.6.2 The Algorithms for Power Flow Analysis are:

2.6.2.1 Gauss-Seidel Method. it is the most commonly used iterative method for solving linear algebraic equations [A]{x}={b}.

2.6.2.2 Fast Decupled Method

2.6.2.3 Decupled Method

2.6.2.4 Newton-Raphson Method

To studies and design of power flow systems, we need a computer program, and information buses are very important (generation, load, mega vars, megawatts, losses). The best method designs, Newton-Raphson method, it is adopted for reducing the base case power flow. To apply the Newton - Raphson method to the solution of the power flow equations, we shall express bus voltages and line admittance in polar form. In the Newton-Raphson load flow, we use Newton's method to compute the voltage magnitude and angle at each bus in the system that satisfied power balance. Solves the polar form of the power flow equations until the ΔP and ΔQ mismatches at all buses fall within specified tolerances. We need to solve the power balance equations [6, 28].

- Advantage of Newton-Raphson method

  - Fast convergence as long as an initial guess is close to a solution.
  - A Large region of convergence.
  - When close to the solution the error decreases quite quickly.

- Disadvantage of Newton-Raphson method

  - Each iteration takes much longer than a Gauss-Seidel iteration.
  - More complicated to code, particularly when implementing sparse matrix algorithms.

$$P_a = |V_a|^2 G_{aa} + \Sigma_{\substack{n-1 \\ n \neq a}}^{N} |V_a V_n Y_{an}| \cos(\vartheta_{an} + \delta_n - \delta_a) \quad (2.22)$$

$$Q_a = -|V_a|^2 B_{aa} - \Sigma_{\substack{n-1 \\ n \neq a}}^{N} |V_a V_n Y_{an}| \sin(\vartheta_{an} + \delta_n - \delta_a) \quad (2.23)$$

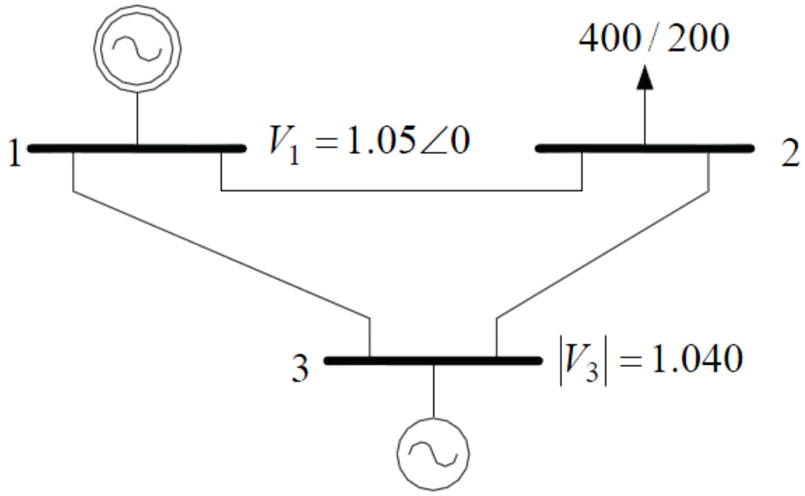


Figure 2.18 Three type of buses [6]

$$Y_{an} = G_{an} + JB_{an} \tag{2.24}$$

$$Y_{an} = \frac{1}{Z_{an}} \quad (Z_{an} = R_{an} + JX_{an}) \tag{2.25}$$

$$\delta_n - \delta_a = \text{zero when } n = a$$

$$I_i = \Sigma_{j=1}^{n} Y_{ij} V_j \tag{2.26}$$

Recall the standard Newton Raphson Method

$$x_n + 1 = x_n - \frac{f(x_n)}{f'(x_n)} \qquad x_n + 1 = x_n + \Delta x_n$$

$$\text{where } \Delta x_n = -\frac{f(x_n)}{f'(x_n)} \qquad \Delta x_n * f'(x_n) = -f(x_n)$$

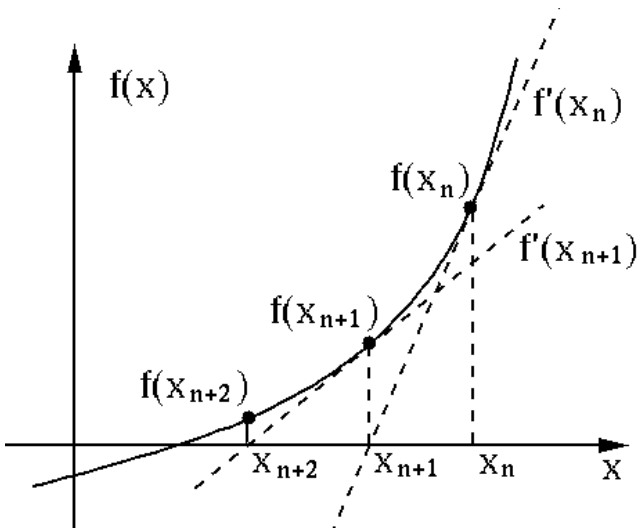


Figure 2.19 Geometrical illustration of the Newton-Raphson method

[http://math.tutorvista.com/calculus/newton-raphson-method.html]

2.7 Power Flow in a Transmission Line

Considering a two bus system example consisting of generator bus S and load bus R and a transmission line between them as shown in fig 2.20 while line resistance is neglected for simplicity, the active power P, and reactive power Q transfer equations for both receiving and sending ends can be written as [17]

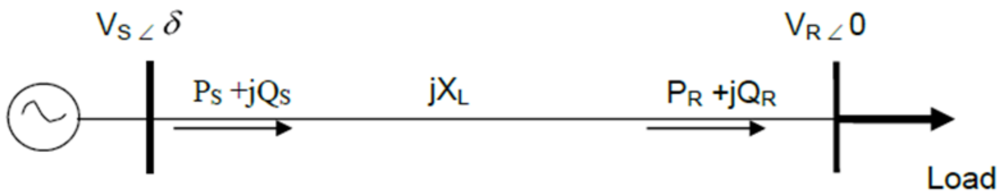


Figure 2.20 Power transfer between two buses [17]

$$V_R = V_S - JXl$$

$$S = P - JQ \Rrightarrow VI \Rrightarrow V\left(\frac{V_S - V_R}{-JX}\right)$$

$$= V_R\angle 0\left(\frac{-V_S\angle\delta + V_R\angle 0}{-JX}\right) = \frac{V_S V_R}{X}sin\delta - j\left(\frac{-V_S V_R}{X}cos\delta + \frac{{V_R}^2}{X}\right)$$

Separating real and imaginary parts we get:

$$P_S = \frac{V_S V_R}{X}sin\delta = P_{Max}sin\delta \tag{2.27}$$

$$P_R = \frac{V_S V_R}{X}sin\delta = P_{Max}sin\delta \tag{2.28}$$

$$Q_S = \frac{{V_S}^2 - V_S V_R\, cos\delta}{X} \tag{2.29}$$

$$Q_R = \frac{-{V_R}^2 + V_S V_R\, cos\delta}{X} \tag{2.30}$$

From equations (2.27) to (2.28) assuming that the power angle between two buses is quite small as well as neglecting line charges, we can see that active and reactive power transfer depends on the following;

- ✓ Sending and receiving end voltages
- ✓ Power angles between the buses
- ✓ Line impedance between the buses

Equations (2.27) and (2.28) suggest that active power transfer between two buses is directly proportional to the angle between them and that when the sending and receiving ends powers are the same, thus the line is lossless. In a practical case, the line has some amount of resistance therefore there is an accompanied active loss. Equations (2.29) and (2.30) suggest that reactive power transfer is dependent on the magnitude of the sending and receiving ends voltages and the reactance of the line. Based on the equations for active and reactive power flow, it is clear that the line parameters limit the current flow. The obvious limitation is the current creating the maximum allowable temperature that is dependent on the properties of the material used. Since the line is operated continuously, it is loaded far below the current limit. The most important limitations to power flow in a line are, therefore [17]

- ✓ Thermal limit
- ✓ Voltage drop limit
- ✓ Transient stability limit
- ✓ Steady state stability limit

For uncompensated medium length lines (>80km) the limiting factor is the voltage drop, whiles for long lines (>320km) the limiting factor is the steady state stability limit. On the other hand, for compensated lines the limiting factor is the thermal limit.

2.8 Techniques for Suitable Inquire Bus to Install RP Controller

Voltage instability is a phenomenon that is dependent on the operating state of the whole power network. The weakest bus is the one that is nearest to experience voltage collapse, to identify a possible collapse situation; a system-wide approach is needed. This section aims to answer how we can find the most suitable bus to install voltage control techniques. There are several technics have been chosen to show a week bus that are:

2.8.1 P-V Curve

Nose curves or P-V curves can be used to illustrate the basic phenomena associated with voltage instability [1]. Nose curves or P-V curves are obtained by plotting the active power transfer P across a grid interface versus the voltage V at a representative bus. By increasing the interface transfer, the voltage of the studied bus will begin to drop as the grid is stressed more and more. Eventually, the power transfer will reach its maximum, and the voltage now drops rapidly as the load demand continues to increase. The power flow solutions will not converge beyond this point, indicating system instability. Knowing the point of instability makes it possible to determine the stability margin of the grid at a certain operating point. These curves are commonly used by grid operators to guarantee that an anciently large margin is kept to accommodate for contingencies. The simple system is shown in Figure 2.21. "Vs" is representing the sending end voltage and "Vr" is representing the receiving end voltage. The two buses are connected via a transmission line that is represented by "Z" [1].

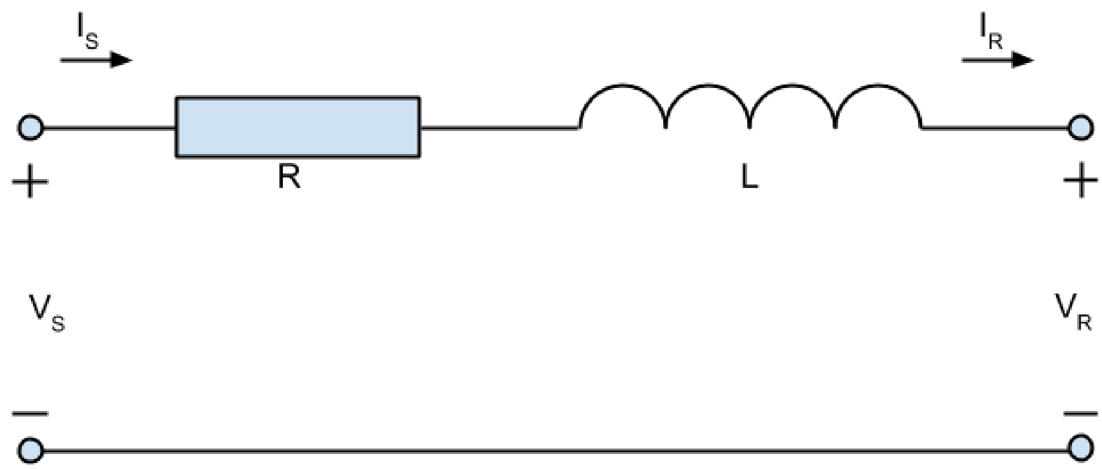


Figure 2.21 Simplified network circuit [17, 38]

The load bus voltage can be represented as following [8]

$$V_r = \sqrt{\frac{{V_s}^2}{2} - \text{ptan}\vartheta \pm \sqrt{\frac{{V_s}^4}{4} - X^2P^2 - x{V_s}^2\text{ptan}\vartheta}} \qquad (2.31)$$

By increasing the load at chosen to bus bar in the system (other loads are fixed) and getting responses from sources until the system reach the limits and get crashes as shown in figure 2.22. This procedure has to follow for each bus bar in the system that required to be investigated. If the load continuously increases more than maximum active power generation, voltage collapse will happen, and the system gets blackout.

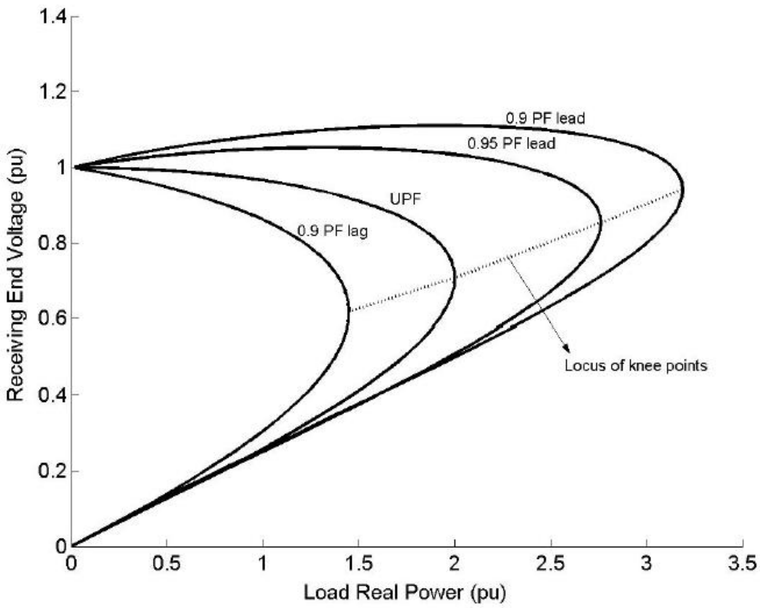


Figure 2.22 Typical PV curve [45]

2.8.2 QV Curve

PV is one of the methods that widely used for stability analysis; it shows how bus voltage affected by variation of active power. To get a better picture, it is can introduce the concept of QV curves. QV analysis shows the sensitivity and variation of bus voltages on reactive power injections or absorptions by loads. It is a plotting of (V & Q), but it is still traditionary called QV curve [1].

$$S = P + JQ \tag{2.32}$$

$$Q = P * \tan\vartheta \tag{2.33}$$

$$V_r \sqrt{\frac{{V_s}^2}{2} - P(\frac{Q}{P}) \pm \sqrt{\frac{{V_s}^4}{4}} - X^2 \left(\frac{Q}{\tan\vartheta}\right)^2 - X{V_s}^2 Q} \tag{2.34}$$

By the same procedure, QV curve can be plotted as shown in figure 2.23. If generation reactive power exceeds limit value (bottom of the curve), voltage collapse will happen.

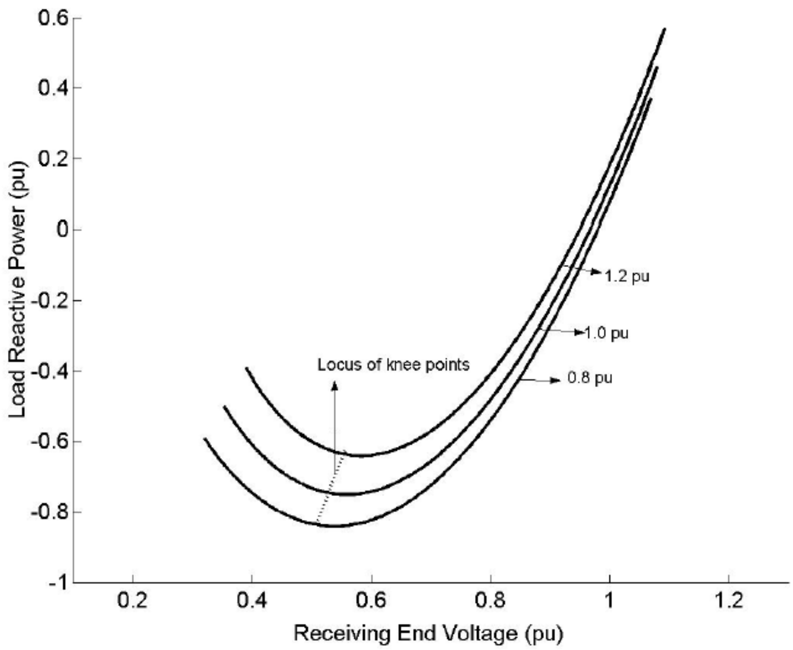


Figure 2.23 Q-V curve for different load real powers [8]

2.8.3. Other Indices

There are also some other methods, but they are not giving good results in our network because KR network have some tie connections, and there are many mobiles that are installed on the lines. Those techniques that listed below depend on the study of power flow through a line between two buses;

- V/Vo Index
- Voltage Stability Index
- Novel Voltage Stability Index
- Line stability index VPCI
- Line stability index LQP
- Line stability index FVSI

2.9 The Per-Unit System

The per-unit system is a fundamental in the analysis of electrical power system since electric elements such as power and voltage are usually in the mega or kilo range in a power system. This is due to a large amount of power transmitted [5]. Other values such as current and impedance are usually represented as a percent or p.u. computed by using a base or reference value. Advantages of the per-unit system are: circuits simplified. pu values are same for all machine regarding their size. {Same p.u for both 10 MVA, 500 MVA}, same ranges for voltages. Per-Unit reluctance for both primary and secondary side remain same. Multiplication of two per units is also per unit, per unit values are same for both three phase and single phase. Per-Unit value remains same for both star and delta connection, finally manufacture values mostly in per unit. Above four quantities (voltage, power, current, and impedance) are expressed on a per-unit basis by the equation [8, 29, and 37]

$$\text{quantity per unit} = \frac{\text{Actual value}}{\text{base value of quantity}} \tag{2.35}$$

$$V_{pu} = \frac{V_{actual}}{V_{base}} \tag{2.35}$$

$$I_{pu} = \frac{I_{actual}}{I_{base}} \tag{2.35}$$

$$Z_{pu} = \frac{Z_{actual}}{Z_{base}} \text{ and } Z_{base} = \frac{V_{base}}{I_{base}} \tag{2.35}$$

$$Z_{pu} = \frac{{kv^2}_{L-L\,\text{nominal or base}}}{MVA_{base}} \tag{2.35}$$

$$I_{base} = \frac{MVA_{base} * 10^3}{\sqrt{3} * kv_{L-L\,\text{nominal}}} \tag{2.35}$$

2.10 Peak and RMS Voltage

Peak-to-peak and peak values are most often used when measuring the amplitude of AC waveforms directly from an oscilloscope display. Peak-to-peak voltage is the voltage value of a sine wave occurs twice each cycle, once at the maximum positive value and once at the negative maximum value unit is volts peak-to-peak (Vp-p). Unit of peak voltage is volts peak (Vp). AC voltmeter shows the RMS value. For a typical sinusoidal waveform, the peak-to-peak voltage is equal to 2 times the peak voltage. A method of translating the varying values of alternating voltage into a constant equivalent value is needed. The effective value of voltage is a common method of expressing the value of AC. This is also known as RMS (root-mean-square) value. If the voltage in the average home, for example, is said to be 22o volts, this is RMS value. For a sine wave, the effective (RMS) value is 0.707 times the peak value and RMS voltage unit is volt [30].

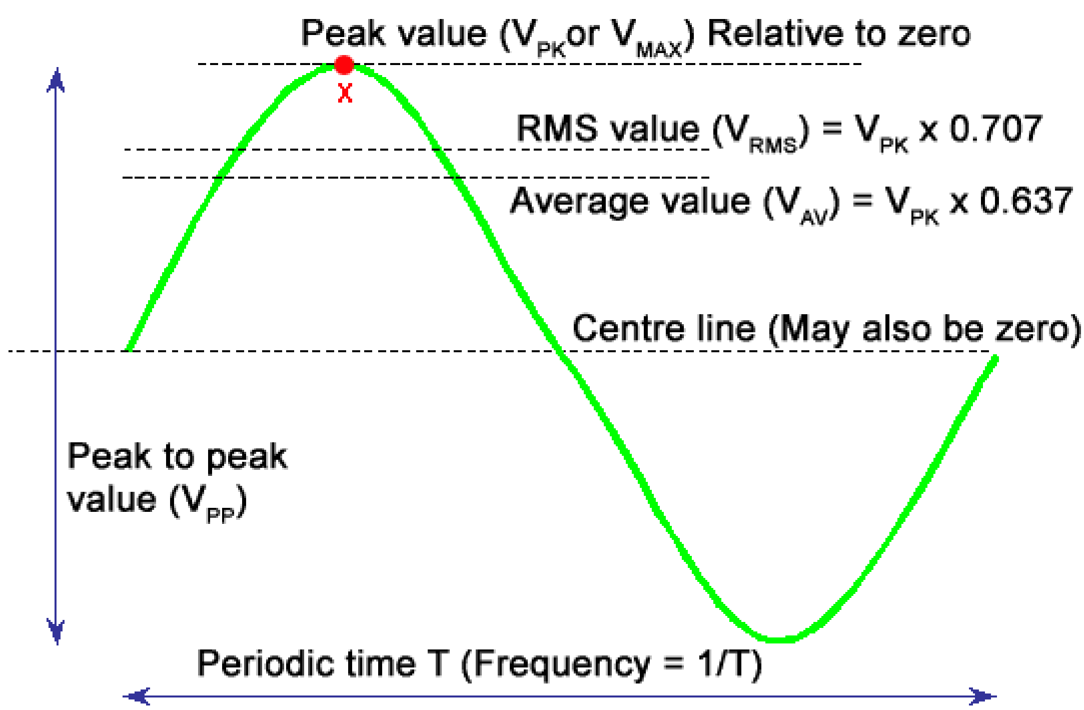


Figure 2.24. Peak-to-peak, peak and RMS voltage [38]

CHAPTER 3

TECHNIQUES FOR REACTIVE POWER AND VOLTAGE CONTROL

Voltage magnitude and reactive power are tightly coupled, reactive power provides the important function for voltage regulating, and voltage is used to push active power through the distribution and transmission system to the customer. A greater reactive demand decreases the bus voltage while reactive generation increases the bus voltages. Voltage and reactive power must be properly controlled and managed to maintain proper stability and provide adequate service quality of the power system. Reactive power is present when the current and voltage are not in phase; one waveform leads the other and Power factor less than unity. Reactive power and voltage control service is a crucial ancillary service used by all system operators for a secure and reliable operation of power systems. The reactive power cannot be transmitted efficiently through long transmission lines because it leads to additional reactive and active power losses in the system. As a result, the voltage and reactive power have to be controlled by using special techniques dispersed throughout the system [7].

3.1 Importance of Voltage and Reactive Power Control

Reactive power compensation and voltage regulation are two effective measures to improve the voltage quality [23]. Both utility and client equipment designed to operate at particular voltage rating, long time operation outside allowable range could cause them damage. Too wide variations of voltage cause excessive heating of electrical equipment such as distribution transformers. The lamp characteristics are very sensitive to changes of voltage, the life of the lamp may be reduced by 50% when voltage fluctuation occur. Also, the power load consisting of induction motors, the voltage variations may cause stray operation. System stability is satisfactory reactive power control, and voltage levels have a significant impact on stability. Ensures transmission system operates efficiently [4, 7, 30].

3.2 Reactive Power Generated

Reactive power produced by the AC power source is saved in a reactor or a capacitor during a quarter of a cycle and in the next quarter of the cycle, it is sent back to the power source. Hence, the reactive power oscillates between the Alternating Current source and the reactor or capacitor so to evade the circulation between the load and source it needs to be controlled. When the load on the system increases, voltage drop increased in synchronous alternator impedance, feeders, transformer impedance and transmission line. These voltage deviations are undesirable and must be kept within the limits by using reactive power control techniques [6, 7].

3.3 Types of Equipment of Voltage and Reactive Power Control

Voltage levels control is accomplished by controlling the absorption and production of reactive power flow at all levels in the system. Generating units supply the basic means of voltage control additional devices to control voltage [5]:

3.3.1 Static Sources or Sinks of Reactive Power:

The reactive power compensation of transmission system is divided into two main groups: Shunt and series reactive compensation.

3.3.1.1 Shunt Compensation

Devices that is connected in parallel with the transmission line or directly connected to bus bars is called the shunt compensation. More reactive power flows from sending end to the receiving end when the load is high; it is cause the large voltage drop in the line. Shunt compensation could be capacitors or reactors, to control or improve the receiving end voltage, bank of capacitors installed at the receiving end to feed and generate the reactive power to the load. The Shunt connected reactors are used to minimize the line overvoltages by absorbing the reactive power; the shunt connected capacitors are used to maintain the voltage at the desired level by compensating the reactive power to the transmission line, improve the voltage quality, enhance the system stability, steady-state transmittable power can be increased. A suitable number of capacitors are switched in during high load condition depending the load demand. Usually, shunt capacitors are used when the power system have lagging power factor [8].

Capacitors are said to generate reactive power because they store energy in the form of an electric field. Therefore, when current passes through the capacitor, a charge is built up to produce the full voltage difference over a certain period.

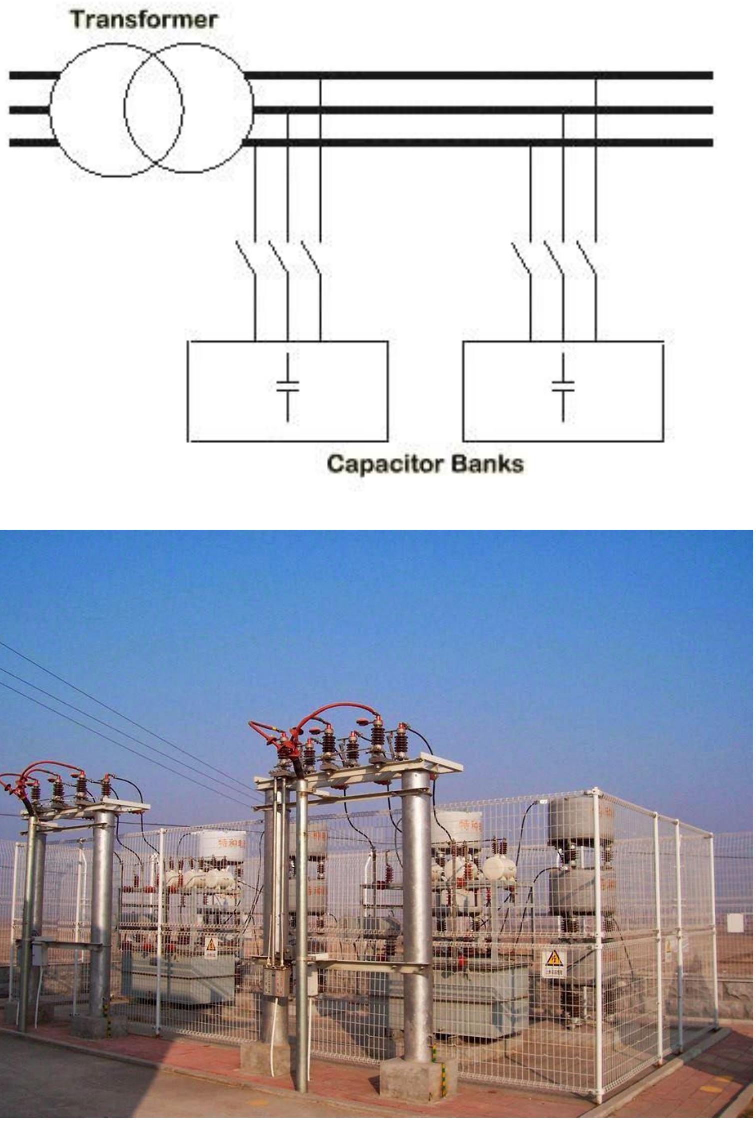


Figure 3.1. Single line diagram and practical shunt capacitor banks

[https://en.wikipedia.org/wiki/Flexible_AC_transmission_system]

3.3.1.2 Series Compensation

Series compensation. When large reactive power flows (current flows) this causes a large voltage drop. There are two modes of operation capacities and inductive mode.Typically series compensation uses capacitors to generate reactive power and to decrease the equivalent reactant of the long transmission line. The disadvantage of the series capacitor is at light load series capacitors have little effect and high voltage production across the capacitor during short circuit current, to avoid this problem special devices (Spark gap and non-linear resistance) are used. A series compensation can be connected anywhere in the transmission It works as a controllable voltage source. The advantage of Series Compensation is an increase in transmission capacity [8].

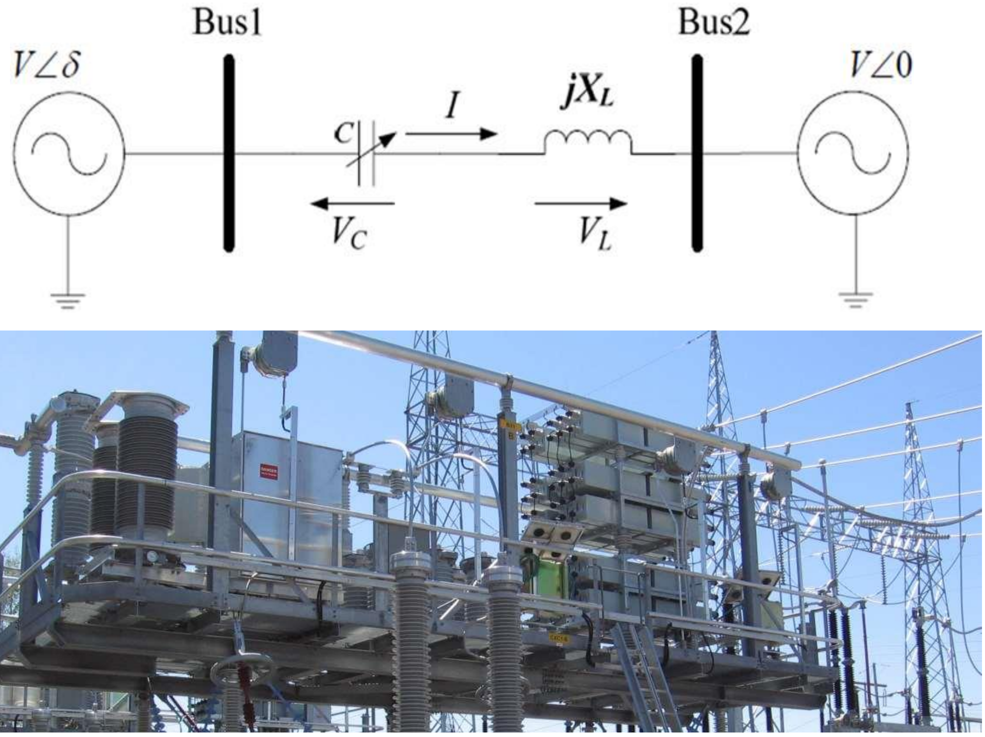


Figure 3.2. Single line diagram and practical series capacitor with transmission line

[http://new.abb.com/facts/fixed-series-compensation]

For the same amount of power transfer and the same value of sending and receiving voltage end the angle in the case of series compensated line is less than that of uncompensated line.

$$p = \frac{V_1 V_2}{X_l} \sin\delta \qquad p = \frac{V_1 V_2}{X_l - X_c} \sin\delta' \qquad \therefore \frac{\sin\delta'}{\sin\delta} = \frac{X_l - X_c}{X_l} = \frac{X_l(1-k)}{X_l} = 1 - k \tag{3.1}$$

A lower angle means better system stability and $k = \frac{X_c}{X_l}$ is a degree of compensation.

3.3.2 Voltage Regulating

Voltage regulation is the capability of a system to provide near constant voltage over a wide range of load conditions.also the voltage regulation is percentage the voltage at no load to the voltage at a full load of a transformer to its full load voltage [5]. The benefits of voltage regulation are reduced system losses by reducing reactive power flow thereby more improvement voltage system and finally, better efficiency of power generation, transmission, and distribution.

$$\text{voltage regulation }\% = \frac{V_{\text{no load}} - V_{\text{full load}}}{V_{\text{full load}}} * 100 \tag{3.2}$$

3.3.2.1 Tap Changing Transformers

Transformer tap changing is the easiest and basic way of voltage control of transmission, sub-transmission and distribution system. The transformer does not produce any reactive power (rather it consumes) and only transfers the reactive power from one side to another side by changing the in-phase component of the system voltage. In this method, some tapings are provided on the secondary of the transformer. The voltage drop in the line is supplied by changing the secondary e.m.f. of the transformer through the adjustment of its some turns. Power transformers are equipped with tap changer that will be used to decrease or increase transformer winding's (usually located at the highest voltage side). As a result, the secondary or output voltage can be regulated. The tap selection may be made on automatic or manual tap changer mechanism. When the position of the tap is changed, the number of secondary turns is varied the voltage varied. When the movable arm makes contact with lower positions such as 1, the output voltage is minimum this during the period of light inductive load, but when the movable arm contact with a higher position such as 5, an output voltage is maximum this during the period of the high inductive load. At heavily load conditions, power system voltages are kept at the highest practical level to decrease reactive power requirements and to increase the effectiveness of shunt capacitors to compensated reactive power. During light load conditions, it is usually required to lower network voltages avoid under the excited operation of generators. There are two main types of tap changers [30, 33]

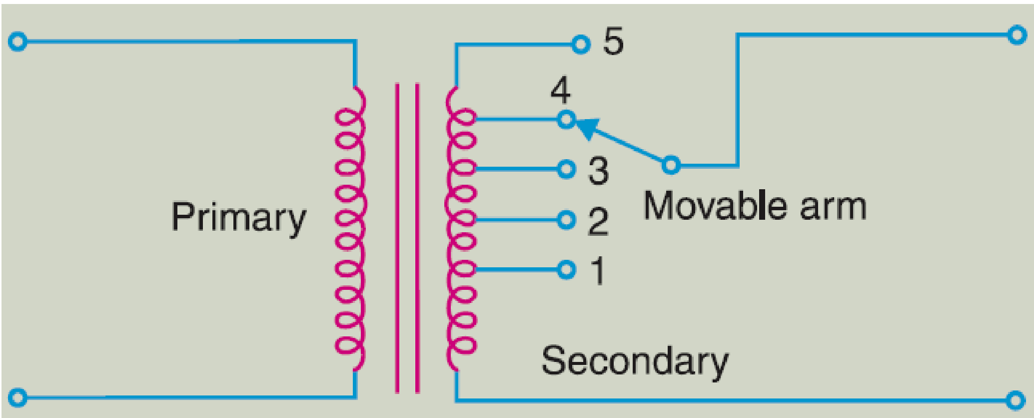


Figure 3.3. Tap changing transformer [33]

- Off-load tap changer is a device used to change the tap position on transformers, which is mostly used for low power and low voltage transformers where long term voltage variation in the system are required, for instance, load growth or seasonal changes. In this type tap, changers can only be changed if it is not energized [33].
- On-load tap changers enable voltage regulation and phase shifting by varying the transformer ratio under load without interruption. Which are mostly used in power transformers having large rating where voltage variations are required to be changed continuously and if there are fluctuation in system voltage. The advantages of this type it can be operated even transformer is loaded. The voltage management of the range + 15 to -15 % can be achieved by tap changing transformers [33].

Disadvantages of transformer tap changer are:

- The Speed of voltage regulation may not be fast enough because of physically moving components.
- Tap changer mechanism components require regular maintenance or replacement of its components.
- Regulation of voltage in limited range.

3.3.2.2 Auto Transformer

The auto transformer has two end terminals with a single winding, one or more terminals at intermediate tap points. The primary voltage is functional across two of the terminals. Result voltage is taken from two terminals, always having one terminal is common with the primary and secondary the current flows directly from the input to the output, and only smaller part inductively. Autotransformers are frequently used in power transmission and distribution [33].

- In a step-down transformer, the source is commonly connected across the full winding while the load is connected by a tap across the required voltage.
- In a step up transformer, the source is connected to a tap across desired voltage, while the load is attached across the full winding.

3.3.3 Dynamic Source

Synchronous motor sometimes called synchronous capacitor or compensate, a condenser is a salient pole without a prime mover, but spins freely, its purpose is not to convert electrical power into mechanical power and via verse. Running at no load to supply reactive power support or to stabilized power system voltage by either absorbing or generating reactive power in receiving end substation. The condenser's installation and operation are identical to large electric motors and generators. Synchronous condensers are used for power factor correction, and they are more economical than capacitors. By controlling the field excitation, it can be made to either generate or absorb reactive power. With a voltage regulator, it can automatically adjust the reactive power output to maintain constant terminal voltage. It draws a small amount of active power from the power system to supply losses. Usually, we can say they are the active shunt compensators and have been used to improve the voltage profile and system stability [33, 41].

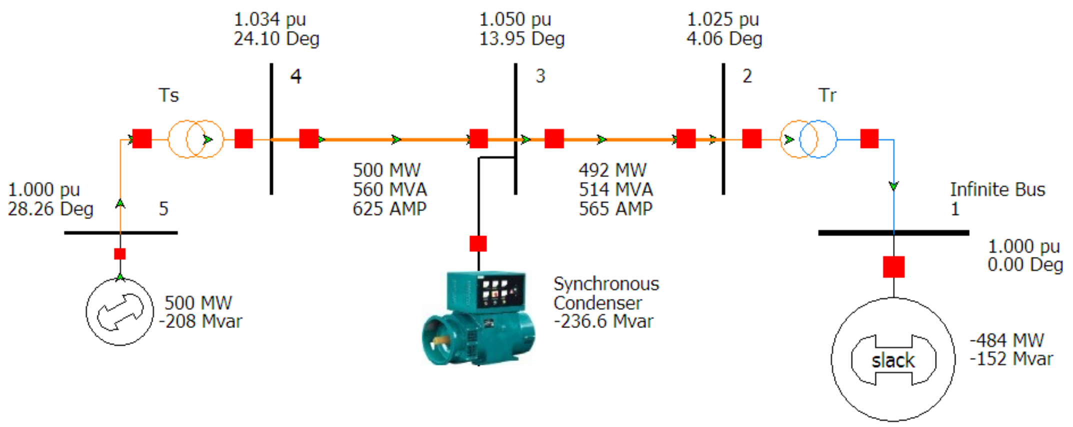


Figure 3.4. Synchronous condenser

[http://www.energyfaqs.com/2015/05/advantage-and-disadvantage-of.html]

3.3.4 Charging Overhead Lines and Cables

Overhead lines and cables are produced Mvar. Total line-charging mega vars specified for each line account for shunt capacitance and equal $\sqrt{3}$ times the rated line voltage in kilovolts times I_{charg} ' divided by 10^3. That is, [3]

$$(\text{Mvar})\ \text{charge} = \sqrt{3} * |V| * I_{charg} * 10^{-3} = wC_r|V|^2 \quad (3.3)$$

Shunt inductive compensation used for charging transmission line [5]

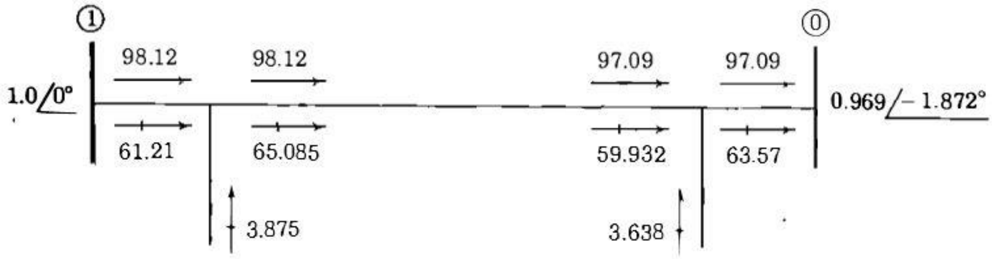


Figure 3.5. Single-line diagram showing a flow of active and reactive power [3]

3.3.5 Phase Shift Transformer (PST)

A phase-shifting transformer is an a special type of three phase auto transformer the phase angle shift between the incoming and outgoing lines without changing the voltage ratio. It is used to supervis the active power flow in the power network by regulating phase angle [5]. These transformers are used in networks where intensive power-wheeling takes place due to deregulation. A phase shifting transformer is a standard transformer with a single primary winding and several secondary windings. The secondary windings are interconnected in such a way as to give a resultant waveform that is shifted in phase from the primary waveform. The secondary windings may be of different sizes from the primary winding to give the desired phase shift. Fig. 3.6. shows an example of a phase shift transformer connection.Various other configurations, such as zig-zag connections of the secondary, are used to achieve the desired effect. Phase shifting can also be applied to cancel out selected harmonics [6].

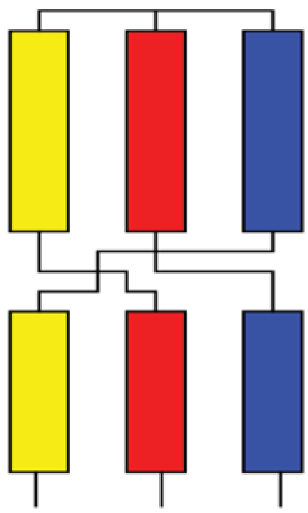


Figure 3.6. Phase shift transformer [5]

3.3.6 Flexible AC Transmission System (FACTS)

Flexible Alternating Current Transmission Systems are controllers based on solid states technologies. The ACTS has various limits increase classified as static limits and dynamic limits. They are incorporating power electronic-based and other static controller techniques to intensify controllability, power transfer capability of AC transmission lines and other quantities in power systems. As per IEEE definition, FACTS controllers: A power electronic based system & other static equipment that supply control of one or more Alternating Current transmission parameters.

Depending on the ports, the FACTS controllers can be classified as [6]

- **Two-port**
  - ✓ Series-Series Controller
    - Interline Power Flow Controller (IPFC)
    - Thyristor controlled phase angle regulator (TCPAR)
  - ✓ Series-Shunt Controller
    - Unified Power Flow Controller (UPFC)
    - Thyristor Controlled Phase Shifter (TCPS)
- **One –port**
  - ✓ Series Controller: FACTS connected in series acts as a controllable voltage source.
    - Thyristor Controlled Series Capacitor (TCSC)
    - Synchronous Static Series Compensator (SSSC)
    - Thyristor –Switched Series Reactor (TSSR)
    - Thyristor –Switched Series Capacitor (TSSC)
    - Thyristor Controlled Series Reactor (TCSR)
  - ✓ Shunt Controller: FACTS connected in parallel acts as a controllable current source.
    - Static Synchronous Compensator (STATCOM)
    - Static Var Compensator (SVC)
      - Thyristor - Switched Reactor (TSR)
      - Thyristor - Switched Capacitor (TSC)
      - Thyristor - Controlled Reactor (TCR)

Depending on the power electronic devices used in power system the FACTS controllers can be classified as [6]

- ❖ Variable impedance type
- ❖ Voltage Source Converter (VSC)

✓ Variable impedance controllers include:

- Static Var Compensator (SVC), (shunt connected)
- Thyristor Controlled Series Compensator or Capacitor(TCSC),(series connected)
- Thyristor Controlled Phase Shifting Transformer (TCPS) (combined shunt-series)

✓ The VSC-based FACTS controllers are:

- Static Synchronous Compensator (STATCOM) (shunt connected)
- Interline Power Flow Controller (IPFC) (combined series-series)
- Unified Power Flow Controller (UPFC) (combined shunt-series)
- Self-commutated compensator (SCC)
- Synchronous Static Series Compensator (SSSC) (series connected)

3.3.6.1 Objectives of FACTS

The concept of FACTS was established to solve the problem that was emerging in power systems in the late 1980s as there are restrictions on the construction of transmission line and to promote power growth of import and export. Within the basic grid security guidelines, the FACTS devices enable the transmission system to obtain one or more of the following benefits [6, 10, 29].

- ➢ Increased system reliability and capacity thereby power quality improvement.
- ➢ Increase the loading capability of lines to their thermal capabilities, including short-term and seasonal demands.
- ➢ Added flexibility in siting new generation.
- ➢ Effective voltage regulation, voltage control and improving voltage profile.
- ➢ Reduce voltage harmonics and voltage drop.
- ➢ Improvement of steady-state power transfers capacity.
- ➢ Improvement of transient stability margin and increased system security.
- ➢ Damping of power oscillations thereby used for economic reasons.
- ➢ Damping of sub synchronous power system oscillations.
- ➢ Reduction in voltage fluctuations, flickers control.
- ➢ Correction power factor by minimizing reactive power demand.

3.3.6.2 FACTS Concept

Power flow studies are of great importance in planning and designing between buses of power system [10]. Transmission lines that are assumed lossless and represented by the reactance XL. The active power (P12) and reactive power (Q12) flow between buses 1 and 2 of a lossless transmission line by phase difference, voltage and line reactance control variables are given by the following equations.

Active power flow $$P_{12} = \frac{V_1 V_2}{x} \sin(\delta_1 - \delta_2) \tag{3.4}$$

Reactive power flow $$Q_{12} = \frac{{V_1}^2}{x} - \frac{V_1 V_2}{x} \cos(\delta_1 - \delta_2) \tag{3.5}$$

Shunt reactive compensation has been most used in the transmission system to regulate the voltage magnitude, more improve the voltage quality, and enhance the system stability. The series reactive compensation aims to control directly the overall series line impedance of the transmission line. Shunt techniques inject current into the system at the point of contact. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only generates or consumes variable reactive power. Series compensation adds a voltage in opposition to the transmission line voltage drop, thereby reducing the line series impedance.

$$P_2 = \frac{V_1 V_2}{X_l - X_c} \sin\delta \tag{3.6}$$

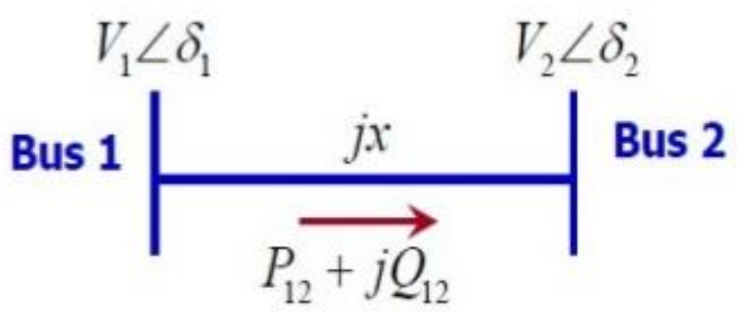


Figure 3.7. Transfer active and reactive power from B1 to B2 [17]

In this thesis, we will use only two shunt techniques in FACTS family namely Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC).

3.3.6.3 Static Var Compensator (SVC)

Static Var Compensator(SVC) is "a shunt device of the Flexible AC Transmission Systems (FACTS) family. A static VAR compensator is a set of electrical devices for providing fast-acting reactive power, power flow control and improve transient stability on high-voltage electricity transmission networks. The SVC is controlling the amount of reactive power generated (injected) into or absorbed by the power system, thereby regulates the voltage at its terminals.By using power electronics.Provide fast-acting reactive power so as to control or maintain specific parameters of the electrical power system. When the power system voltage is low, the SVC generates reactive power (SVC capacitive). When the power system voltage is high, it absorbs reactive power (SVC inductive). SVC includes one or more banks of switched or fixed shunt reactors or capacitors, of which Thyristors switch at least one bank.regulate the line voltage by electronically switching an inductor or a capacitor in shunt with the transmission line [6, 28, 29, 32]. Unlike a synchronous condenser which is a rotating electrical machine, a static VAR compensator has no significant moving parts [28].

- SVCs are used in two main locations [28]
  - Connected to the electrical power system, to regulate the transmission voltage (Transmission SVC)
  - Connected near large industrial loads, to improve power quality (Industrial SVC)

- Static VAR compensator consists and principle [6, 18]
  - Thyristor Controlled Reactor (TCR). Mainly used to keep the voltage down by absorbing VARs from capacitive or light load system.
  - Thyristor Switched Reactor (TSR).
  - Thyristor Switched Capacitor (TSC). Add VARs to an inductive load system.
  - MSC = Mechanically-Switched Capacitor.
  - MSR = Mechanically-Switched Reactor.
  - FC = Fixed Capacitor.
  - Harmonic Filters. Eliminated harmonic distortions.

3.3.6.3.1 The SVC Controller System Consists of

- A measurement system using to measuring the positive-sequence primary power system voltage that should be controlled. A Fourier-based measurement system using a one-cycle running average is used.

- A voltage regulator that uses to compare the reference voltage Vref and the measured voltage Vm thereby obtain voltage error. Voltage error uses to determine the SVC susceptance that needed to maintain the system voltage constant range.

- A distribution unit that computes the TSCs (and eventually TSRs) that must be switched in and out, and calculates the firing angle α of Thyristor Controlled Reactors.

- A synchronizing system using the secondary voltages synchronized with a phase-locked loop (PLL) and a pulse creator that send appropriate pulses to the valve thyristors.

Phasor type of Static Var Compensator is a phasor model, and it is must be used with the phasor simulation method, make active with the powergui block. It can be used in three-phase power systems together with synchronous motors, generators, and dynamic loads to perform transient stability analysis and monitor impact of the SVC on electromechanical oscillations and transmission capability. Phasor type model does not include detailed representations of the power electronics, the synchronization system or the measurement system. A detailed model of an SVC using three TSCs and one TCR [32].

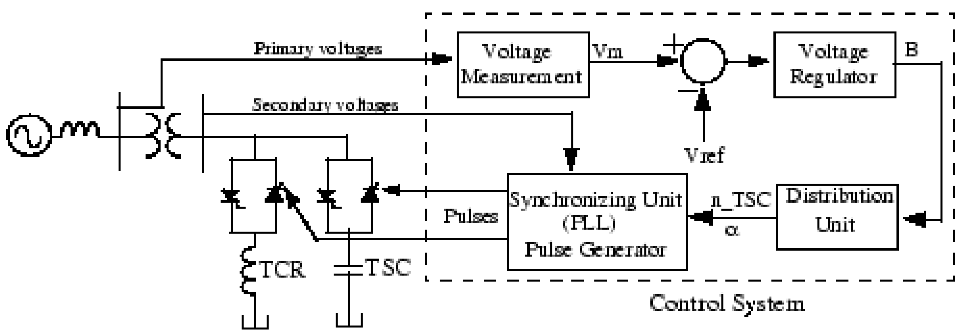


Figure 3.8. Static Var compensator (SVC) with control concept [32, 46]

In an electric power transmission system, a thyristor controlled reactor (TCR) is a reactance connected in series with a bidirectional thyristor valve. If the power system's reactive load is capacities (leading), the SVC will use thyristor controlled reactors to consume VAR from the system, lowering the system voltage. It is usually a three-phase assembly, normally connected in a delta arrangement to provide partial cancelation of harmonics. The main TCR reactor is separated into two halves, with the thyristor valve connected between the two halves. This protects the vulnerable thyristor valve from damage due to flashovers, lightning strikes, etc.

➢ A TCR comprises two main items of equipment:
  - Reactor: It is air-cored (although iron-cored reactors are possible). It is used to limit the peak current.
  - Thyristor valve: The thyristor valve usually consists of 5-20 inverse-parallel-connected pairs of Thyristors connected in series.

The inverse-parallel junction is needed because most commercially attainable thyristors can conduct current in only one direction. The series connection is needed because the maximum voltage rating of commercially available thyristors (up to approximately 8.5 kV) is not enough for the voltage at which the TCR is connected.

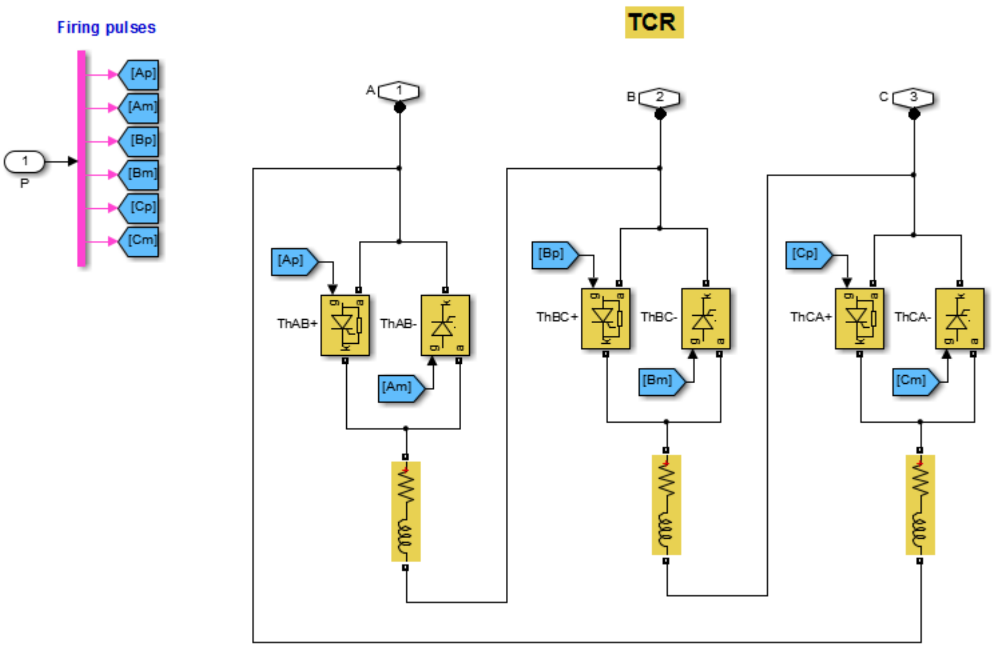


Figure 3.9. Thyristor controlled reactor [32]

A thyristor switched capacitor (TSC) is one type of equipment in electrical power systems that used for compensating reactive power, that consists of a power capacitor connected in series with a bidirectional thyristor valve and, usually, a current limiting inductor (reactor). The thyristor switched capacitor is an important component of a Static VAR Compensator (SVC), where it is often used in conjunction with a thyristor controlled reactor (TCR). If the power system's load is inductive (lagging) conditions, the SVC will use the capacitor banks are automatically switched in to generate VAR to the system, thus a higher system voltage.

The thyristor switched capacitor (TSC), first introduced by ASEA in 1971, is a shunt connected capacitor that is switched OFF or ON using thyristor valves.

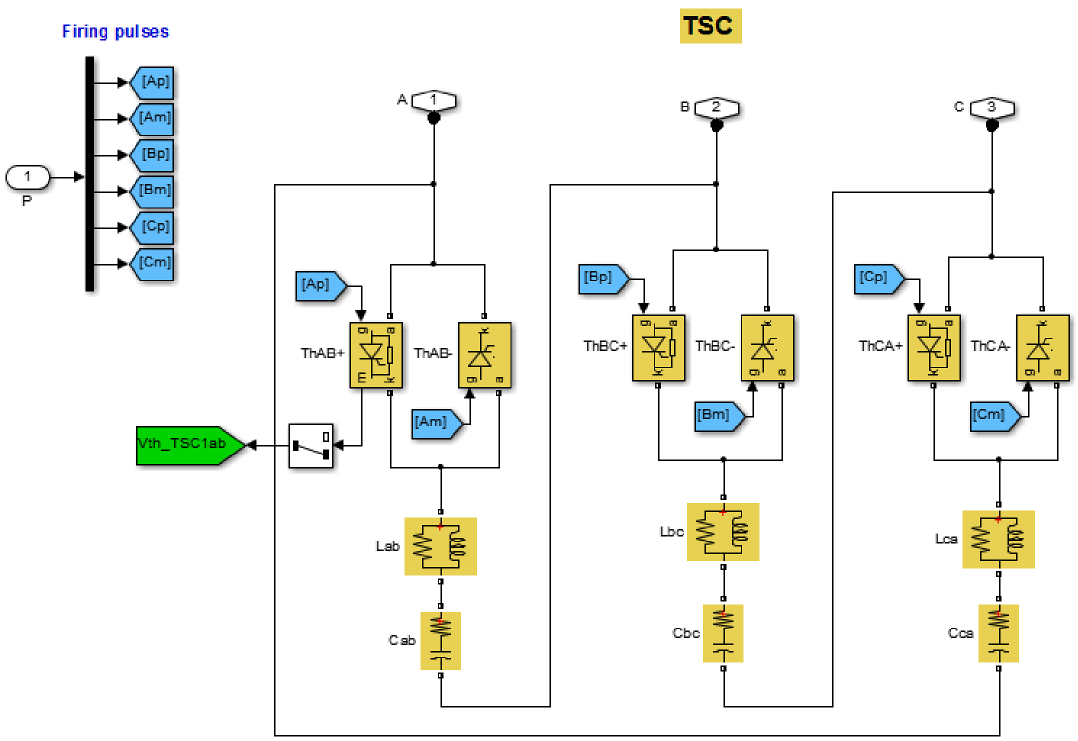


Figure 3.10. Thyristor switched capacitor [32]

Disadvantages of SVC are, once a capacitor in a transmission line gets damaged, and then the entire power flow scheme is interrupted, have limited overload capability, the critical or collapse voltage becomes the SVC-regulated voltage Instability happens once a limit is reached, maintenance is difficult and expensive.

3.3.3.6.2 V-I Characteristic

Static Var Compensator can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits)
- Invar control mode (the SVC susceptance is kept constant).

When the SVC is operated in voltage regulation mode, it implements the following V-I characteristic.

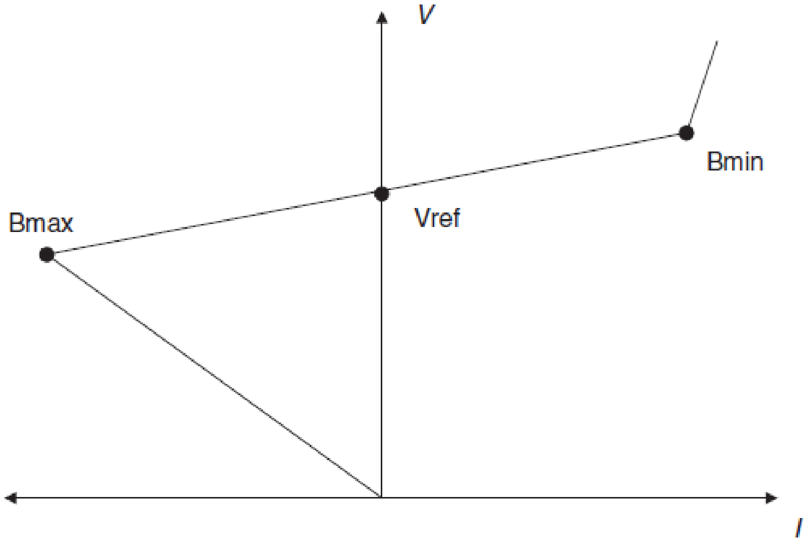


Figure 3.11. SVC V-I Characteristic with three equations [21, 36]

$$V = \frac{I}{B_{C\,Max}} \qquad SVC\ is\ full\ Capacitive\ (B = B_{C\,Max}) \tag{3.7}$$

$$V = \frac{I}{B_{l\,Max}} \qquad SVC\ is\ full\ inductive\ (B = B_{l\,Max}) \tag{3.8}$$

Where:

V: Positive sequence voltage (pu)

I: Reactive current (pu/Pbase) (I > 0 indicates an inductive current)

Xs: Slope or droop reactance (pu/Pbase)

Bcmax: Maximum capacitive susceptance (pu/Pbase) with all TSCs in service, no TSR or TCR

Blmax: Maximum inductive susceptance (pu/Pbase) with all TSRs in service or TCRs at full conduction, no TSC

Pbase: Three-phase base power specified in the block dialog box

As long as the SVC susceptance (B) stays within the minimum and maximum susceptance values imposed by the total reactive power of reactor banks (Blmax) and capacitor banks (Bcmax), the voltage is regulated at the reference voltage Vref. Anyway, a voltage droop is normally used (usually between 4% and 1% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. The above three equations describe the V-I characteristic.

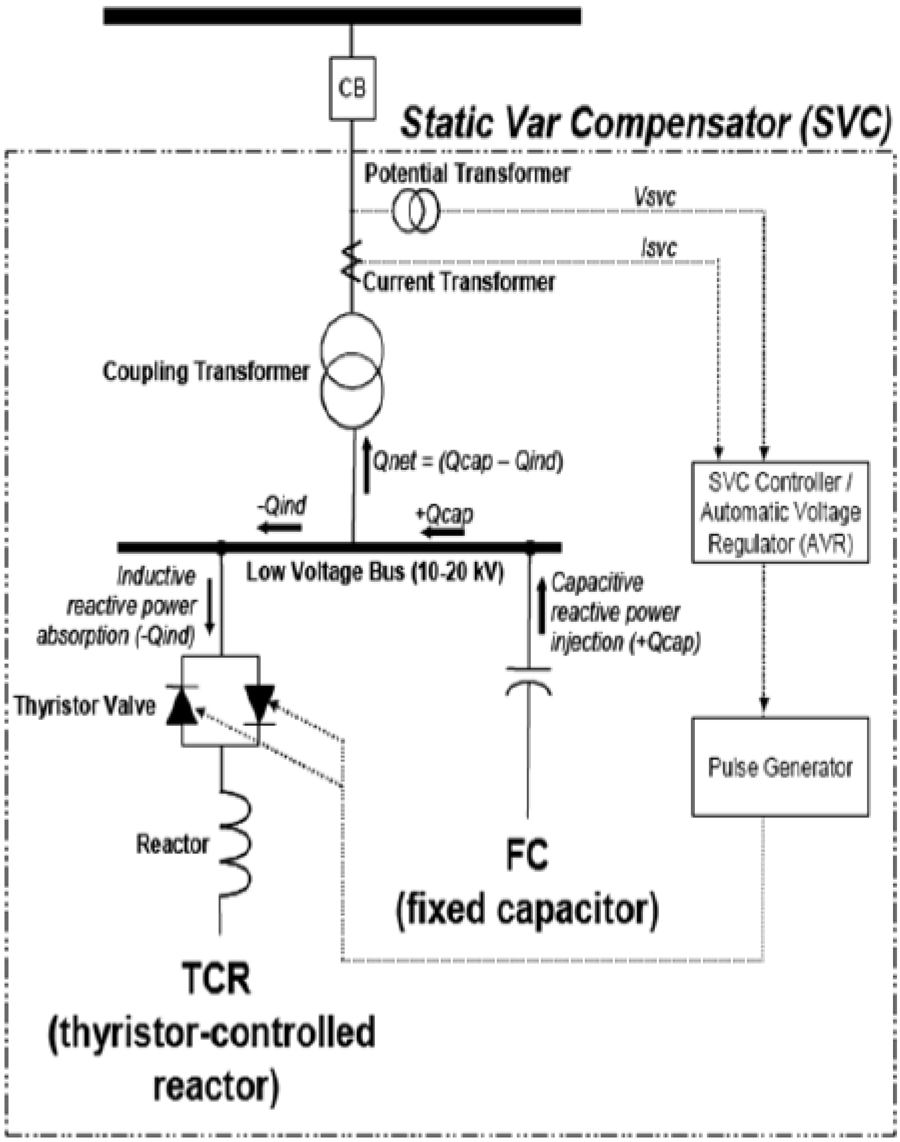


Figure 3.12 SVC with control concept [42]

3.3.6.4 Static Synchronous Compensator (STATCOM)

A static synchronous compensator (STATCOM), also known as a static synchronous condenser (STATCON) [28], is a member of the flexible alternating current transmission system (FACTS) devices and is a regulating device [28]. STATCOM is a voltage-source converter based device that converts a DC input voltage into an AC output voltage to compensate the reactive power needs of the system and is shunt-connected to AC electricity distribution and transmission power systems. The VS is created from a DC capacitor, and the STATCOM can exchange reactive power with the network [6]. Whether a DC source of power is connected across the capacitor, It can also supply some active power to the network. An STATCOM is normally installed in the electric networks with poor power factor or poor voltage regulation to improve these problems. Also, it is used to improve the voltage stability of a network [6, 21].

STATCOM is a regulating device used in a power system, When two AC sources of the same frequency are connected through a series inductance, reactive power flows from higher voltage magnitude AC source to lower voltage magnitude AC source and active power flows from leading source to lagging source. Active power flow is determined by the phase angle difference between the sources, and the reactive power flow is computed by the voltage magnitude difference between the sources. Hence, It can control reactive power flow by changing the fundamental component of the converter voltage on the AC bus bar voltage both phase wise and magnitude wise [27].

STATCOM is defined by IEEE as “a self-commutated switching power converter supplied from an appropriate electric energy source and operated to reproduction a set of adjustable multiphase voltage, which may be coupled to an AC power system with the objective of exchanging independently controllable real and reactive power.”

3.3.6.4.1 Typically STATCOM Consists of a

- Voltage Source Converter (VSC)
- DC energy storage device (capacitor)
- System controller
- coupling transformer and AC filter

Different modes operation of STATCOM [5]

- Capacitive operation mode. When the power system voltage is lower than the voltage of the voltage source converter, the STATCOM generated the reactive power to the system.
- Inductive operation mode. When the power grid voltage is higher than the voltage of the voltage source converter, STATCOM absorbs the reactive power from the system.

Essentially The STATCOM consists of a step-down transformer to step-down the voltage to protection STATCOM Electronics' device, with a leakage reactance, a three-phase IGBT or GTO voltage source inverter (VSI) [31], and a DC capacitor. The difference AC voltage across the leakage reactance produces reactive power exchange between the power system and STATCOM, such that the AC voltage at the bus bar can be adjustable to improve the voltage profile of the power system that is the primary duty of the STATCOM. For enhancing power system oscillation stability, a secondary damping function can be added into the STATCOM. An STATCOM can be used for voltage regulation in a network, having as an ultimate goal the increase in active transmittable power, and improvements of steady-state transmission characteristics and the overall stability of the system. The controller is used to minimize or completely diminish transmission line overvoltage under light load conditions, on the other hand, under heavy loading conditions it can be also used to maintain certain voltage levels.

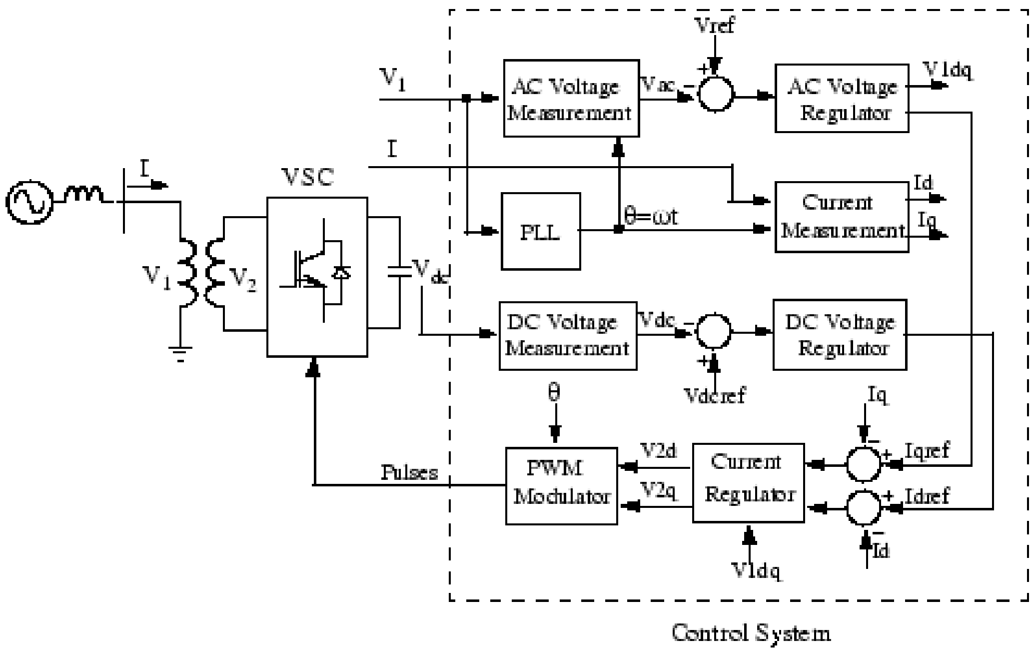


Figure 3.13. Single-line diagram of an STATCOM and control system diagram [46]

3.3.6.4.2 The Control System of STATCOM

- A phase-locked loop (PLL) which synchronizes on the positive-sequence component of the three-phase primary voltage V1. The output of the PLL (angle =ωt) is used to compute the direct-axis and quadrature-axis components of the AC three-phase voltage and currents (labeled as Vd, Vq or Id, Iq on the diagram).

- Measurement systems measuring the d and q components of AC positive-sequence voltage and currents to be controlled as well as the DC voltage Vdc.

- An outer regulation loop consisting of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage regulator is the reference current Iqref for the current regulator (Iq = current in quadrature with a voltage that controls reactive power flow). The output of the DC voltage regulator is the reference current Idref for the current regulator (Id = current in phase with the voltage that controls active power flow).

- An inner current regulation loop consisting of a current regulator. The current regulatory controls the magnitude and phase of the voltage generated by the PWM converter (V2d V2q) from the Idref, and Iqref reference currents produced respectively by the DC voltage regulator and the AC voltage regulator (in voltage control mode). The current regulator is assisted by a feed forward type regulator that predicts the V2 voltage output (V2d V2q) from the V1 measurement (V1d V1q) and the transformer leakage reactance. All steps showed in figure 3.13.

STATCOM, by injecting current in parallel with transmission line could control bus voltage and active power. Also, required active power for a series section is supplied by a DC-link capacitor. For this purpose, the STATCOM sampling from DC-link capacitor voltage as well as the STATCOM connected bus voltage and then by converting these values to dq0 parameters by Parks transformation and calculating voltages in per unit as follows [6, 9]:

$$V_{base} = \sqrt{{V_d}^2 + {V_q}^2} \tag{3.9}$$

Vbus and Vdc are compared by distinct values according to the block diagram depicted in Figure. 3.13. And generate error signals as follows:

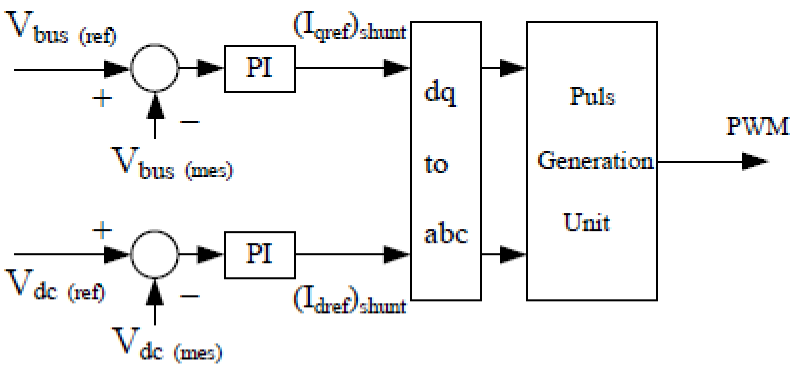


Figure. 3.14. STATCOM control system [9]

Generated error signals carried to PI controllers, and output of PIs converted to abc parameters again and entered to the PWM pulse generating unit. By adjusting control parameters of PI and switching, finally, error signals carried to zero. And accordingly Vbus and Vdc stabled in their reference values [32].

3.3.6.4.3 STATCOM V-I Characteristic

The STATCOM can be operated in two different modes [32]

• In voltage regulation mode (the voltage is regulated within limits).

• In var control mode (the STATCOM reactive power output is kept constant).

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic.

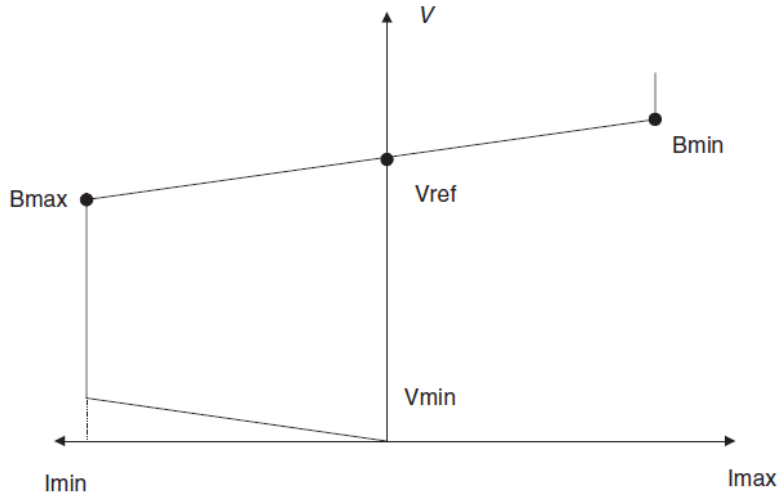


Figure 3.15 STATCOM V-I Characteristic [13, 21, 46]

As long as the reactive current stays within the minimum and minimum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. In the voltage regulation mode, the V-I characteristic is described by the following equation [18, 32]:

V = Vref + Xs I (3.10)

Where

V Positive sequence voltage (pu)

I Reactive current (pu/Pnom) (I > 0 indicates an inductive current)

Xs Slope or droop reactance (pu/Pnom)

Pnom Three-phase nominal power of the converter specified in the block dialog box

3.3.6.5 Cost of FACTS Controllers

Although FACTS controllers can offer high-speed control for enhancing electric power system, one significant disadvantage of power electronic based controllers is more expense per unit of rating than that of similar conventional equipment. The total cost also depends on the size of fixed and controlled portion of the FACTS controllers.Table 3.1 confer an idea at the expense of the various controller. The FACTS equipment cost represents only half of the total FACTS project cost. Other expenses like civil works, installation, commissioning, insurance, engineering and project management constitute the other half of the FACTS project cost [44].

Table 3.1: Expenses comparison of different FACTS controllers [13]

FACTS CONTROLLERS	**expense (US $)**
Shunt capacitor	8$ per one KVAR
Series capacitor	20$ per one KVAR
Static Var Compensator	40$ per one KVAR Controlled portions
TCSC	40$ per one KVAR Controlled portions
Static Synchronous Compensator	50$ per one KVAR
UPFC series portions	50$ per one KVAR through power
UPFC shunt portions	50$ per one KVAR controlled

CHAPTER 4

PRESENT RESULTS OF THE NORTH OF IRAQ'S POWER SYSTEM WITH SVC AND STATCOM

This chapter is given simulation results for comparison of voltage regulation, current and power flow with and without shunt FACTS compensator.

4.1 Voltage Regulation with and without Shunt FACTS Compensator

To evaluate the voltage support provided by an STATCOM and SVC, which are connected to the weakest grid. Figure 4.11. Figure 4.12. And figure 4.13**.** Showed the simulation system that includes a load supplied by the local synchronous generator as well as from the installed two hydropower plant and three 29 MW diesel power plant. The power system is studied to evaluate the system performance under different transient conditions such as:

4.1.1 A Three Phase Fault,

4.4.2 A Sudden Load Change.

When the power system is not compensate receiving, voltages are not at an acceptable level. Table 4.1 presented the Voltage per unit without and with the single shunt (SVC, STATCOM) FACTS controller at three times (Before a three phase fault, during a three phase fault and after a three phase fault).

4.1.1. A Three Phase Fault

Case 4.1.1.1: Converter rating of STATCOM 146 MVA–droop (pu) =0.03 - Vac regulator gain Kp =0.5 and Ki =500 and reactive power limits of SVC 146 MVAR and -146 MVAR. time fault 0.2 to 0.3 second when STATCOM is connect and 0.2 to 0.36 when SVC is connect, time simulation 0.6 second. This case measured voltage for bus 15 (Soran substation) before, during and after fault with reference voltage.

Table 4.1 Voltage p.u for bus 15 (Soran substation) before, during and after fault

Type of controller	Before fault	During fault	After fault
Without controller	0.9508	0.8022	0.9508
With SVC	0.9938	0.8395	0.9938
With STATCOM	1.001	0.8467	1.001

A figure below presented voltage response at bus 15 (Soran substation) in the north of Iraq's power system for three different cases with and without a single shunt FACTS (SVC, STATCOM) controllers. The red color is a voltage reference; yellow is voltage response by STATCOM controller, blue is voltage response by SVC controller and green is voltage response without a controller.

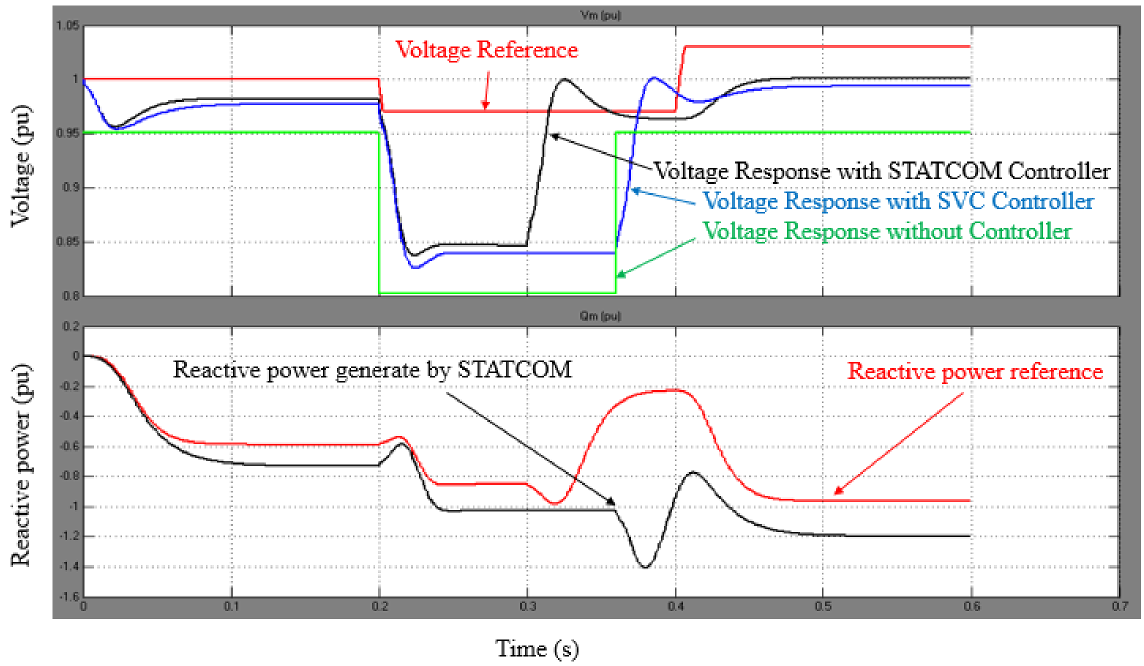


Figure 4.1 Measured voltage for the case 4.1.1.1

The simulation outputs reveal that the reactive power achieved for STATCOM is better when compared with SVC at the 132 KV Soran substation of the north of Iraq's power system. Of course, when the fault occurs STATCOM have better response and voltage obtained is 1 pu.

Table 4.2 Voltage response for the case 4.1.1.1

Type of controller	voltage response at 0.46 second until 0.61second(pu)
Without controller	0.9508
With SVC	0.99
With STATCOM	1

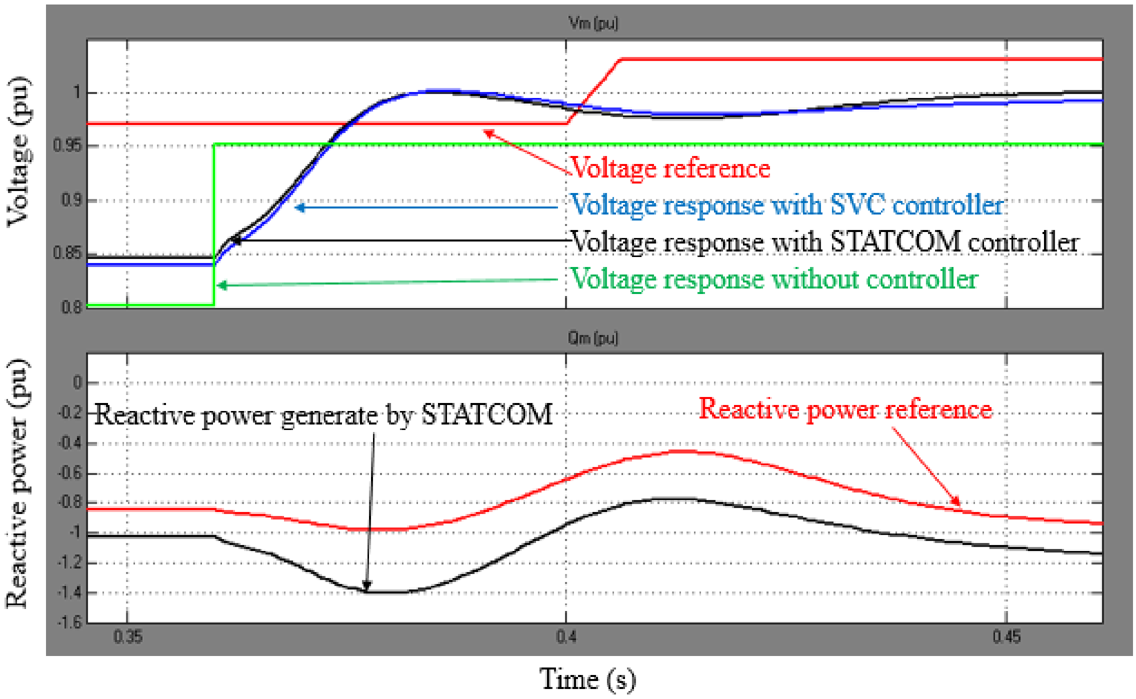


Figure 4.2 Voltage response at 0.46 second until 0.61second for the case 4.1.1.1

The total capacitance of the DC links in farads. This capacitance value is related to the STATCOM rating and the DC link nominal voltage. Energy stored in the capacitance (in joules) divided by the STATCOM rating (in VA) is a time duration [32] that is usually a fraction of a cycle at nominal frequency. For example, for the default parameters, (C=375 µF, Vdc=40 000 V, Snom=100 MVA) this ratio is 3.0 ms. If change the default values of the nominal power rating and DC voltage, you should change the capacitance value accordingly. (C*Vdc^2)/2=3Snom

C: total capacitance of the DC link in farads

Vdc: DC links nominal voltage and

Snom: the nominal power rating

Table 4.3 Voltage transient response for the case 4.1.1.1

Type of controller	transient voltage response(pu)
Without controller	0.9508
With SVC	1.0025
With STATCOM	1

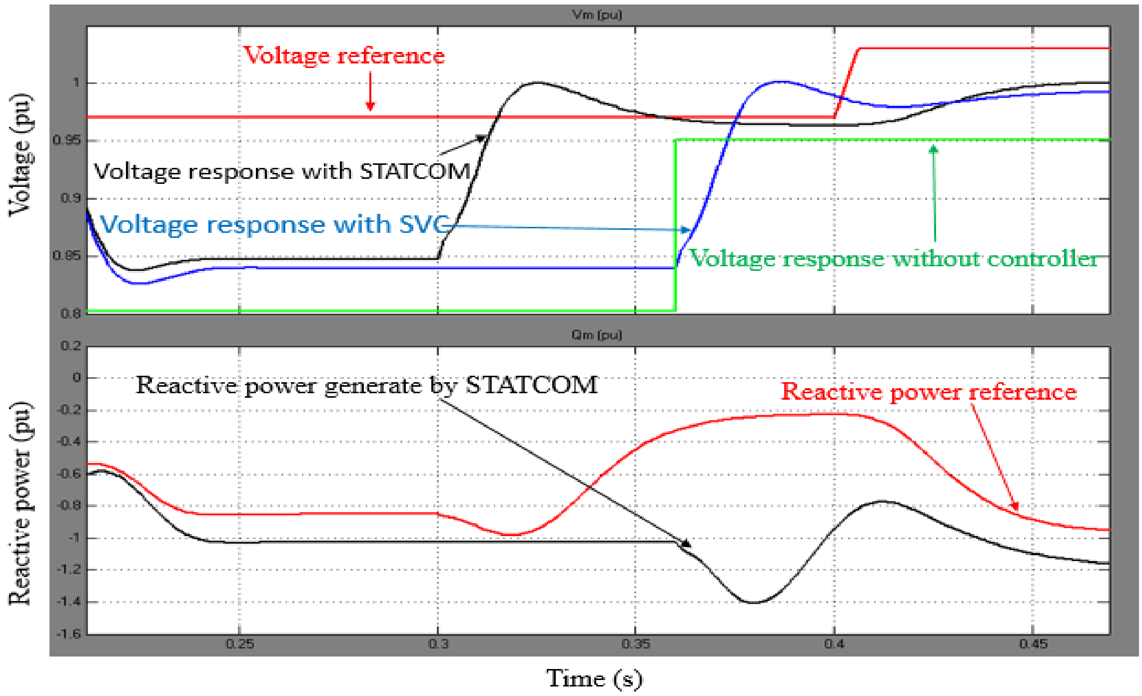


Figure 4.3 Voltage transient response for the case 4.1.1.1

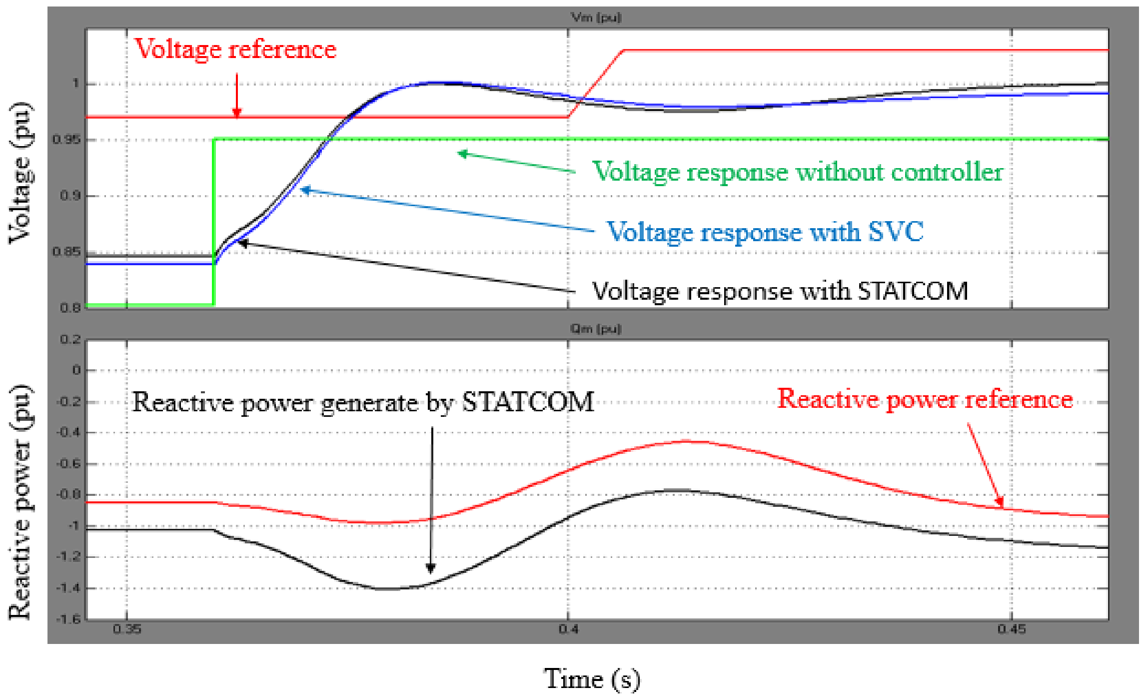


Figure 4.4 Voltage response of STATCOM and SVC for the case 4.1.1.1

<u>Case 4.1.1.2</u>: Converter rating of STATCOM 146 MVA–droop (pu) =0.03 - Vac regulator gain Kp =5 and Ki =1000 and reactive power limits of SVC 146 MVAR and -146 MVAR. Time fault 0.2 to 0.36 second, time simulation 1 second. This case measured voltage at transient voltage response and at steady state for bus 15 (Soran substation)

When we change the value of Vac regulator, gain Kp from 0.5 to 5 or 20 and Ki from 500 to 1000 or 5000. We observed that transient voltage is decreased, but don't change voltage and transfer active and reactive power at steady state.

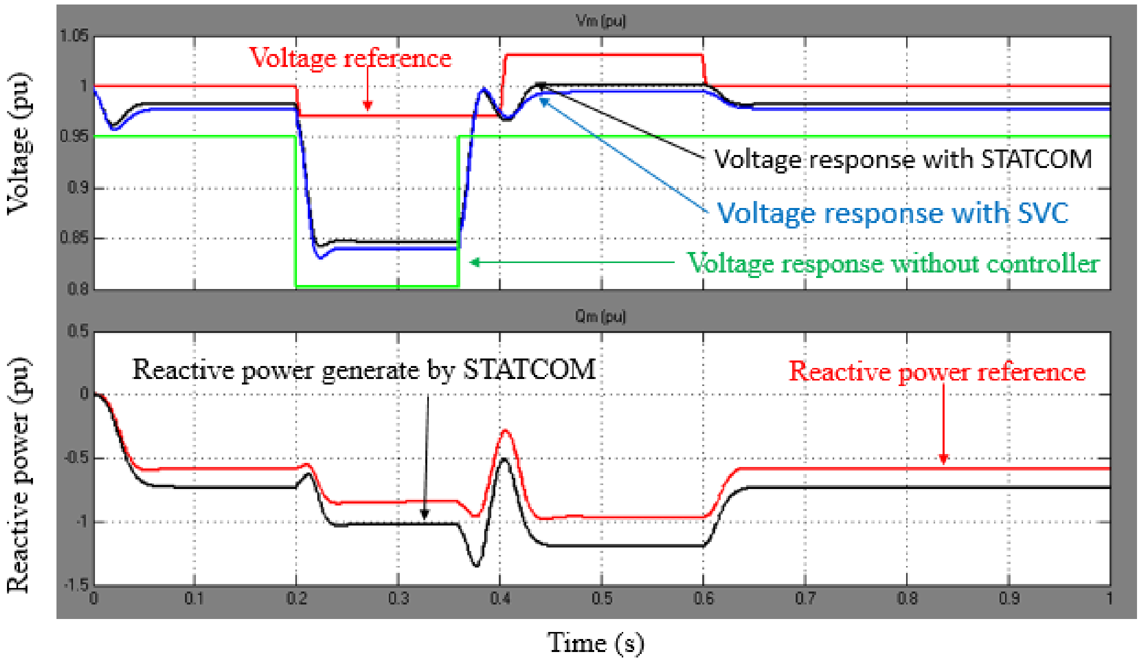


Figure 4.5 Voltage transient response for the <u>case 4.1.1.2</u>

Table 4.4 Voltage transient response for the <u>case 4.1.1.2</u>

Type of controller	Voltage at steady state (pu)	transient voltage response(pu)
Without controller	0.9508	0.9508
With SVC	0.994	1.001
With STATCOM	1.001	0.996

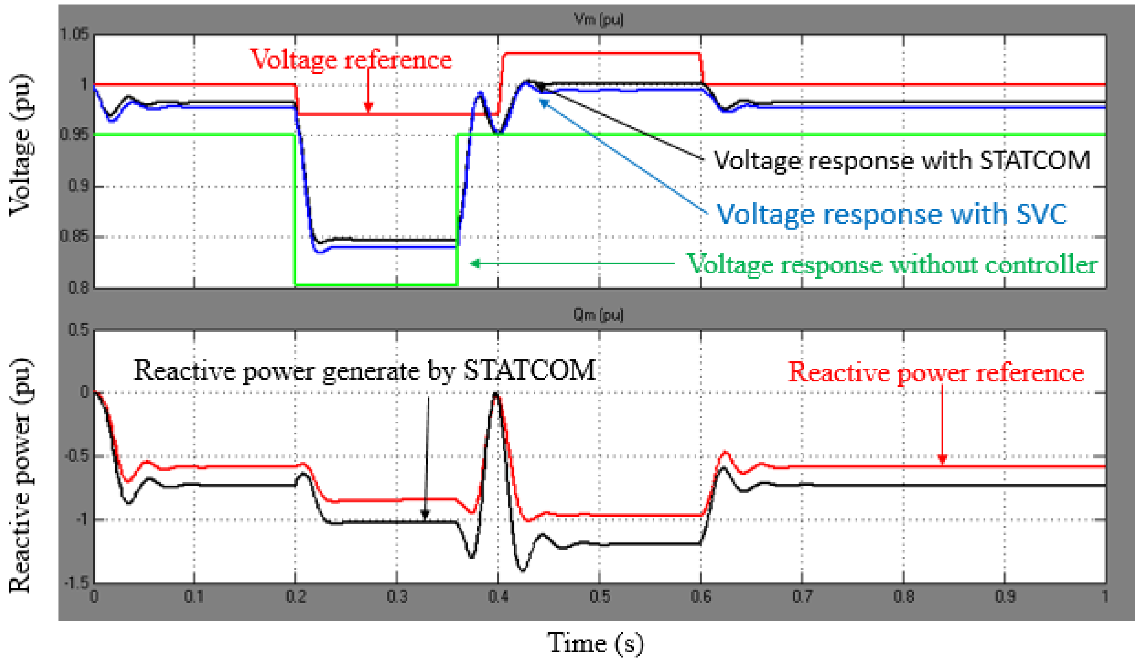


Figure 4.6 Voltage transient response at Vac RG KP=20 and Ki=5000

Table 4.5 Voltage transient response at Vac RG KP=20 and Ki=5000

Type of controller	Voltage at steady state (pu)	transient voltage response(pu)
Without controller	0.9508	0.951
With SVC	0.994	0.998
With STATCOM	1.001	0.988

Case 4.1.1.3: Converter rating of STATCOM 146 MVA–droop (pu) =0.00 - Vac regulator gain Kp =0.5 and Ki =500 and reactive power limits of SVC 146 MVAR and -146 MVAR. In this case have two fault, first time faults 0.1 to 0.17 and second time fault 0.2 to 0.36 second. Time simulation is 1 second. This case measured voltage for bus 15 (Soran sub.) before, during and after a double fault. In this case, we can observe that the voltage response by STATCOM at 0.022 second and during a fault is faster than voltage response by SVC but, at transient response SVC is better than STATCOM because, with the voltage sourse converter, STATCOM has no delay associated with the thyristor firing of SVC. Finally, at steady state has the same voltage response.

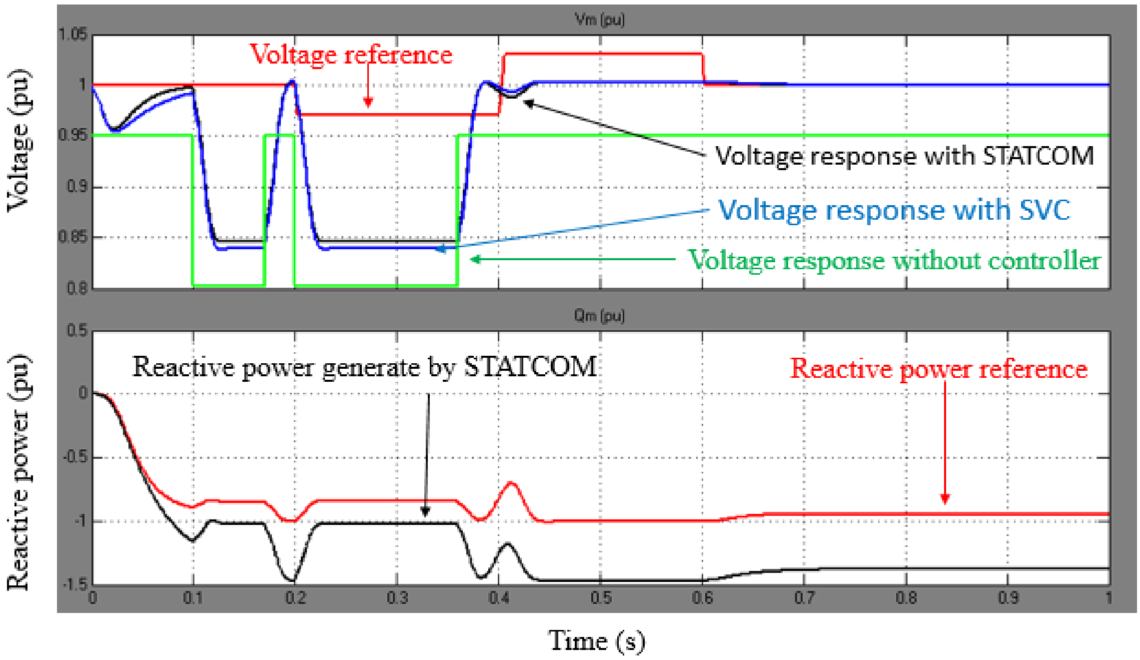


Figure 4.7 Measured voltage for the case 4.1.1.3

Table 4.6 Voltage response at steady state (pu) for the case 4.1.1.3

Type of controller	voltage response at steady state (pu)
Without controller	0.951
With SVC	1
With STATCOM	1

4.1.2. A suddenly load change

When a load of Soran substation suddenly changed, of course, random variations in the magnitude of the bus voltage occur and should be controlled. Standards limit the quantities of starting currents and load fluctuations of equipment to monitor the level of voltage fluctuations. The following figures are presented the voltage response at the suddenly load of B15 changed without and with a single shunt FACTS (SVC, STATCOM) controllers.

Case 4.1.2.1: Converter rating of STATCOM 146 MVA–droop (pu) =0.03 - Vac regulator gain Kp =0.5 and Ki =500 and reactive power limits of SVC 146 MVAR and -146 MVAR. Time suddenly load change 0.5 to 0.7 second, time simulation is 1 second.

Table 4.7 Voltage response p.u for the case 4.1.2.1

Type of controller	Normal situation	Load suddenly changed situation	Normal situation
Without controller	0.9664	0.9508	0.9665
With SVC	0.9849	0.9696	0.9849
With STATCOM	0.9879	0.9736	0.9879

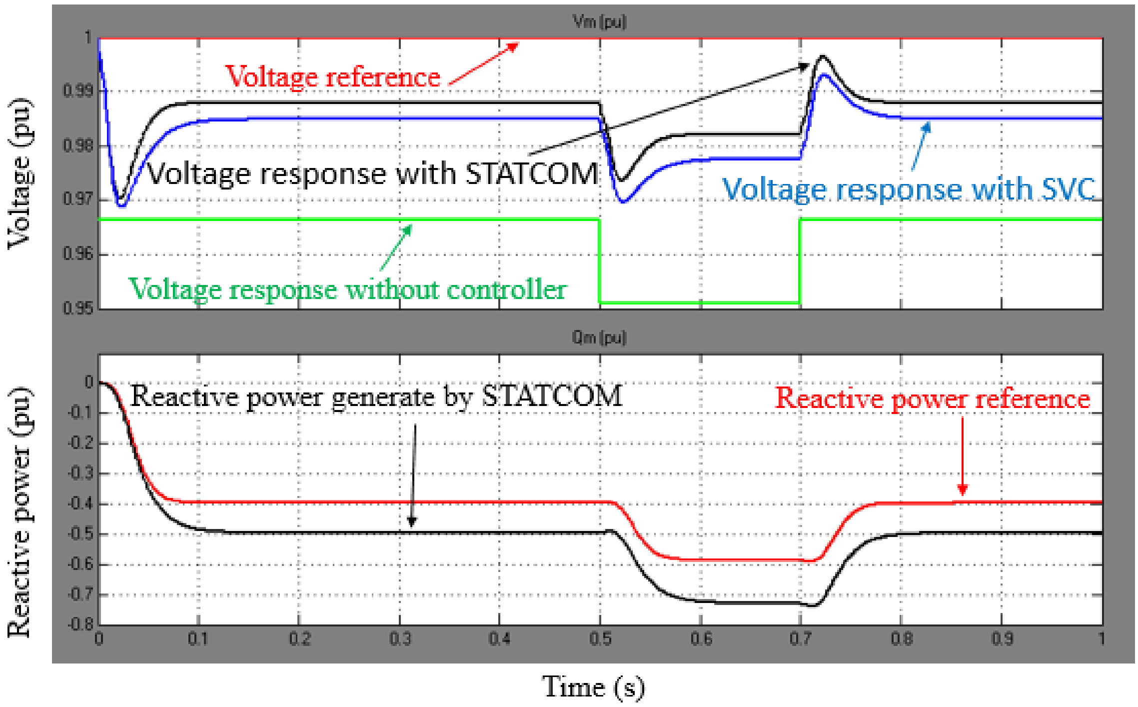


Figure 4.8 Voltage response for the case 4.1.2.1

Case 4.1.2.2: Converter rating of STATCOM 146 MVA–Droop (pu) =0.03 - Vac regulator gain Kp =5 and Ki =1000 and Reactive power limits of SVC 146 MVAR and -146 MVAR. Above two techniques connect with bus 15 (Soran substation) to power flow and voltage control. Time suddenly load change 0.5 to 0.7 second, time simulation result is 1 second.

Table 4.8 Voltage response p.u for the case 4.1.2.2 (Kp =5 and Ki =1000)

Type of controller	Normal condition	Load suddenly changed situation	Normal condition
Without controller	0.9664	0.9508	0.9664
With SVC	0.9849	0.9709	0.9849
With STATCOM	0.9879	0.9754	0.9879

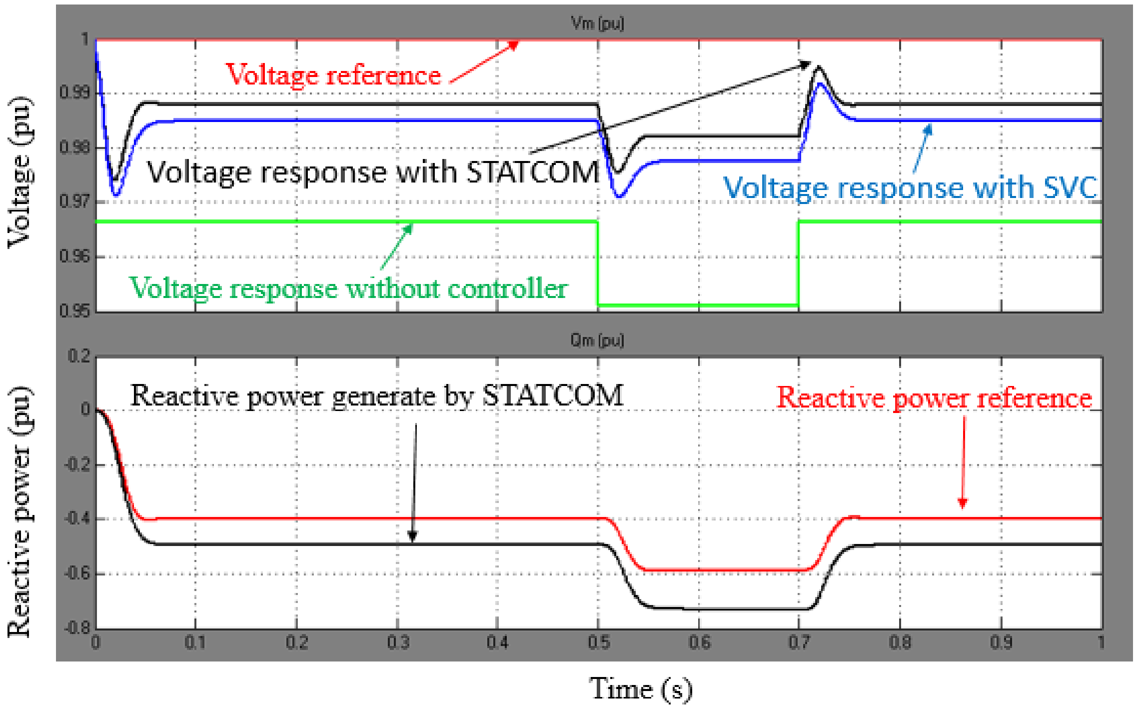


Figure 4.9 Voltage response for the case 4.1.2.2

Table 4.9 Voltage response p.u for the case 4.1.2.2 (Kp =20 and Ki =5000)

Type of controller	Normal condition	Load suddenly turned	Normal condition
Without con.	0.9664	0.9508	0.9664
With SVC	0.9849	0.9729	0.9849
With STATCOM	0.9879	0.9780	0.9879

<u>Case 4.1.1.3</u>: Converter rating of STATCOM 146 MVA–Droop (pu) =0.00 - Vac regulator gain Kp =0.5 and Ki =500 and Reactive power limits of SVC 146 MVAR and -146 MVAR. This case at a suddenly load of B15 changed, above two techniques connect with bus 15 (Soran substation) to power flow and voltage control. Time suddenly load change 0.5 to 0.7 second, time simulation result is 1 second.

Table 4.10 Voltage response p.u for the case 4.1.1.3

Type of controller	Normal condition	Load suddenly turned	Normal condition
Without controller	0.9664	0.9508	0.9664
With SVC	1	0.9844	1
With STATCOM	1	0.9856	1

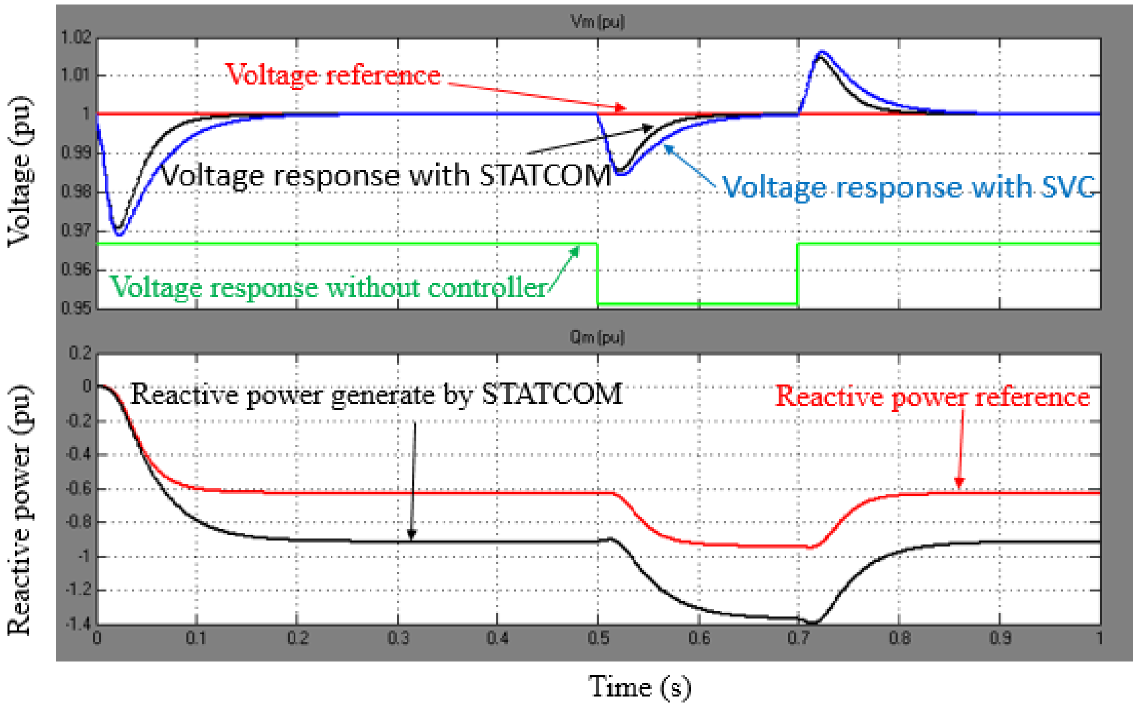


Figure 4.10 Voltage response for the case 4.1.1.3

Table 4.11 Voltage response for case 4.1.1.3. And normal condition.

Type of controller	Normal condition	Load suddenly turned	Normal condition
Without controller	0.9664	0.9665	0.9664
With SVC	1	1.0162	1
With STATCOM	1	1.0146	1

From case 4.1.1.1 the results presented that STATCOM will frequently exhibit a faster response than the SVC because, with the VSC, STATCOM has no delay associated with the thyristor firing of SVC. Performs of the STATCOM the same function as the SVC. However, at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC.

All above cases, explained and presented the effects of two shunt FACTS techniques when connect with the 132KV Soran substation, for voltage response in this bus, north of Iraq's electric power system. At three phase fault occur and suddenly load increase and without controller.

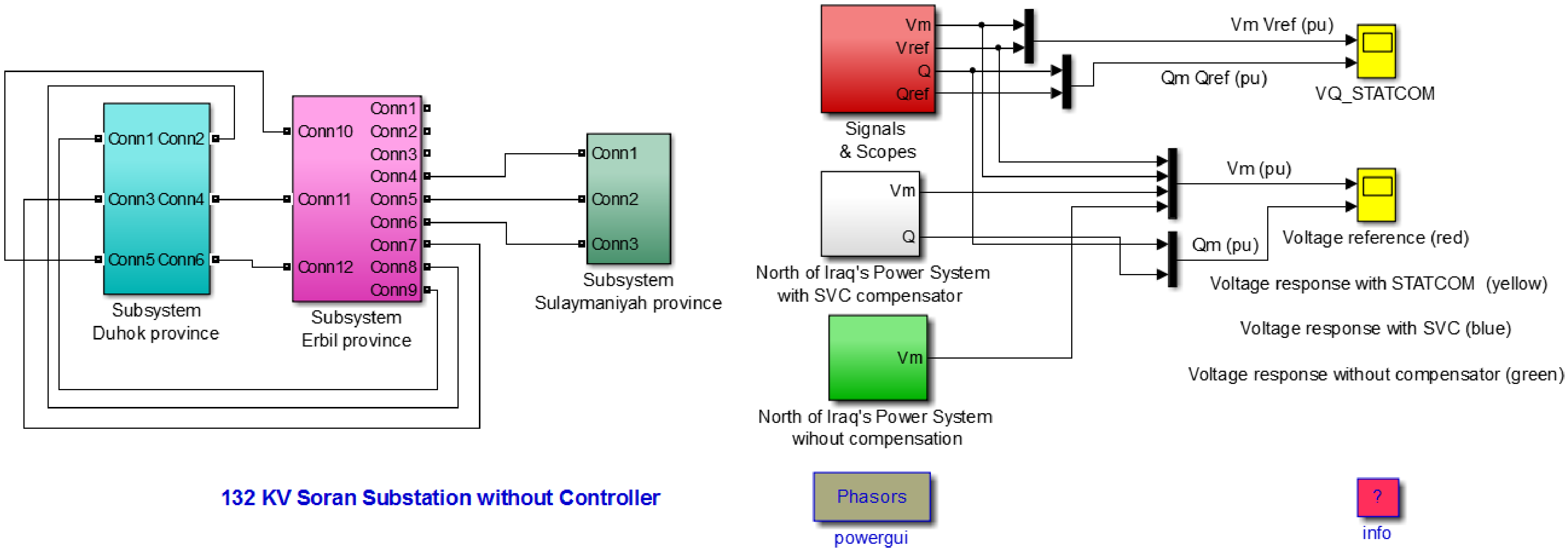


Figure 4.11. The north of Iraq's power system without controller

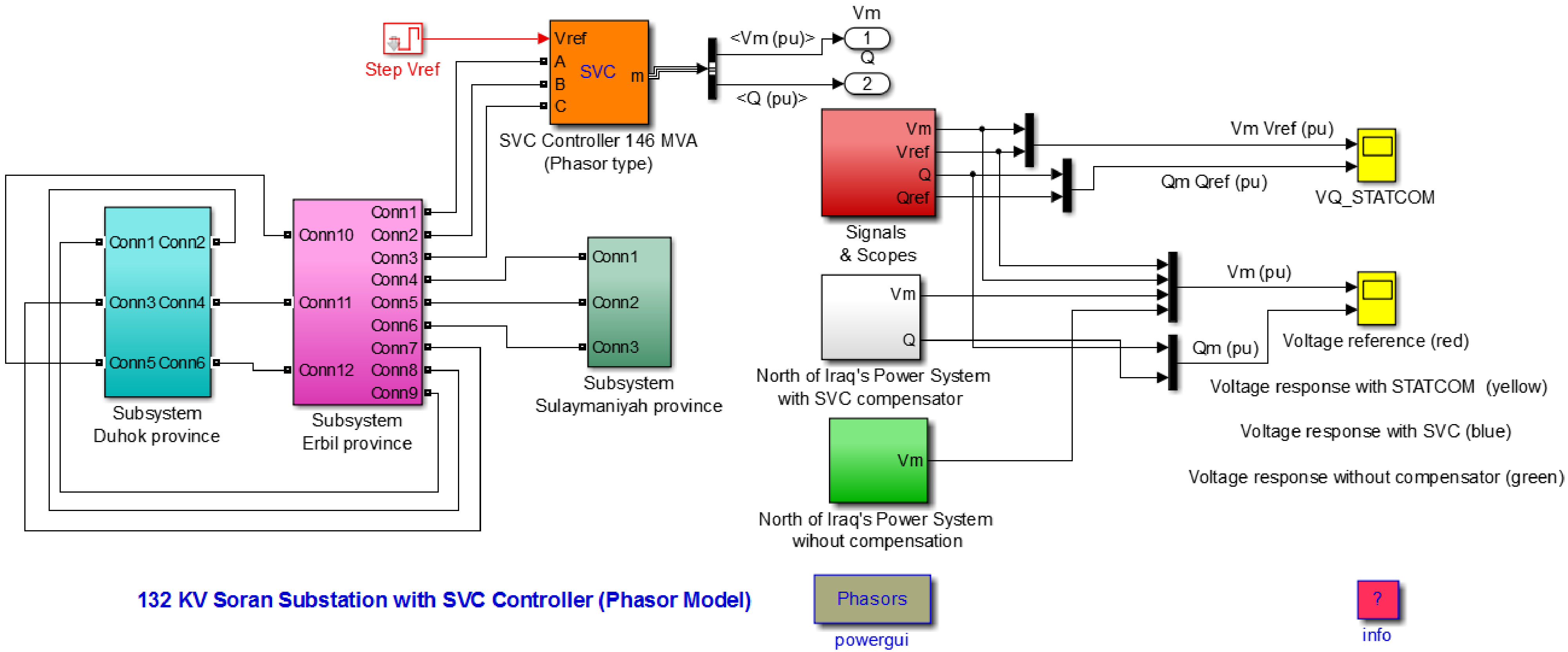


Figure 4.12. The north of Iraq’s power system with SVC controller

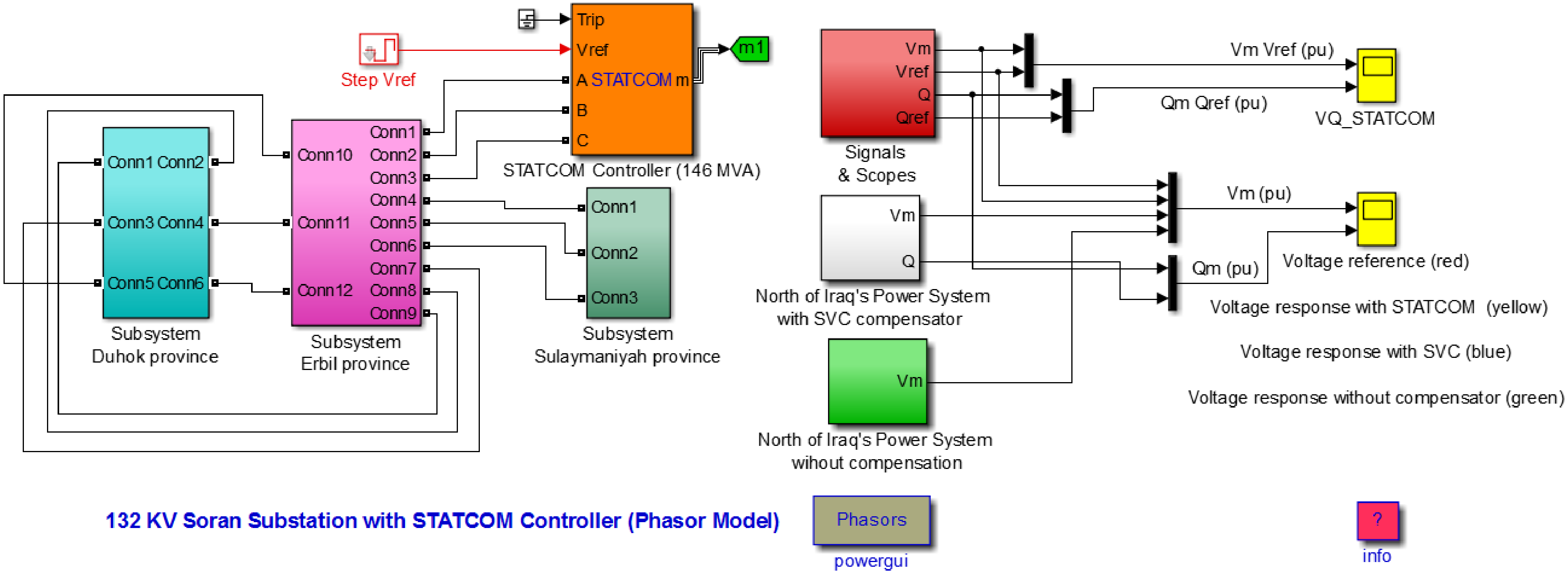


Figure 4.13. The north of Iraq's power system with STATCOM controller

4.2 Current and Power Flow with and without Shunt FACTS Controller

Voltage and power must be delivered reliably from the source to the loads without any disturbance and within the constraints placed on the system operation by reliability consideration, the system will be operated most economically, and Transmission line's transmitting capability will be increased. To obtain above goal FACTS has been added to the north of Iraq's network at the weakest bus "Soran substation.” under different transient conditions such as a three phase fault and a sudden load change.

4.2.1. A Three Phase Fault

The three phases are short-circuited through equal fault impedances. The vectorial sum of fault currents is zero, as a symmetrical fault is considered and there is no path to ground [5].

$$I_a + I_b + I_c = 0 \tag{4.1}$$

As the fault is symmetrical:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_f & 0 & 0 \\ 0 & Z_f & 0 \\ 0 & 0 & Z_f \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4.2}$$

In this thesis obtained simulation results for current and power flow with and without shunt FACTS compensator only when a three phase fault occurs because the result has the same idea.

<u>Case 4.2.1.1</u>: Converter rating of STATCOM 146 MVA–Droop (pu) =0.03 - Vac regulator gain Kp =0.5 and Ki =500 and Reactive power limits of SVC 146 MVAR and -146 MVAR. Time fault 0.2 to 0.36 second, time simulation result is 1 second. Above two techniques connect with bus 15 (Soran substation) to power flow and current control.

Table 4.12 Simulation results with and without controller at B15

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	125.5	0.9508	88.84	72.31	429.1
SVC	129	0.9772	10.2	126.1	462.1
STATCOM	129.6	0.9818	-3.28	135.8	494.2

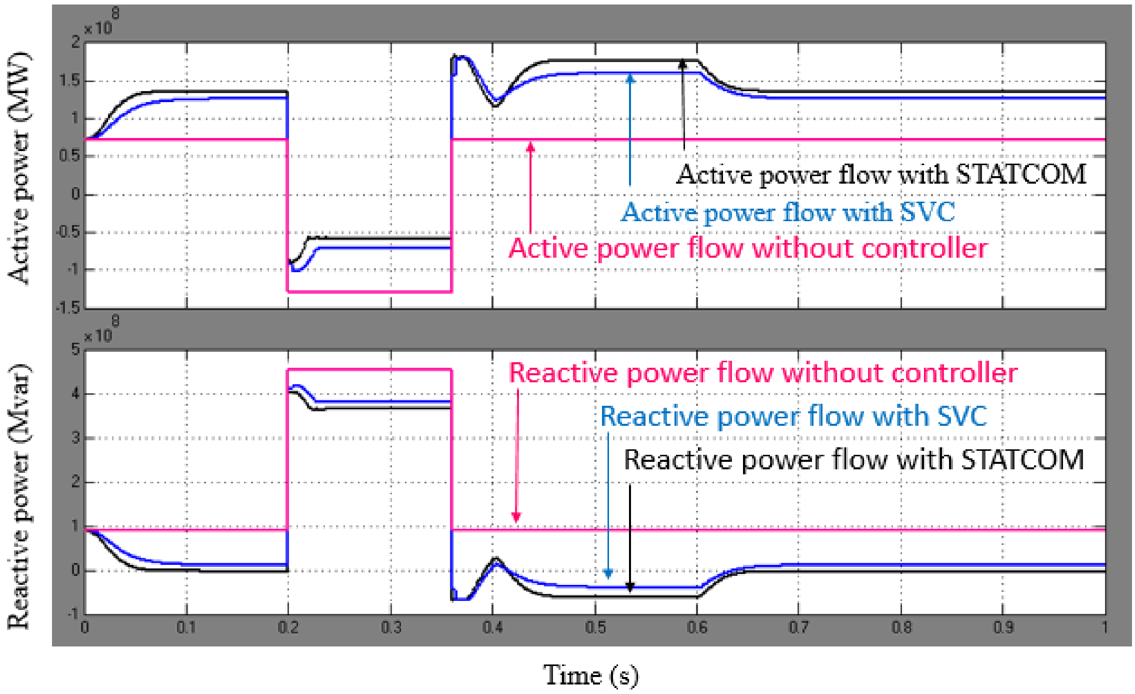


Figure 4.14. Power transfer B15 with and without controller

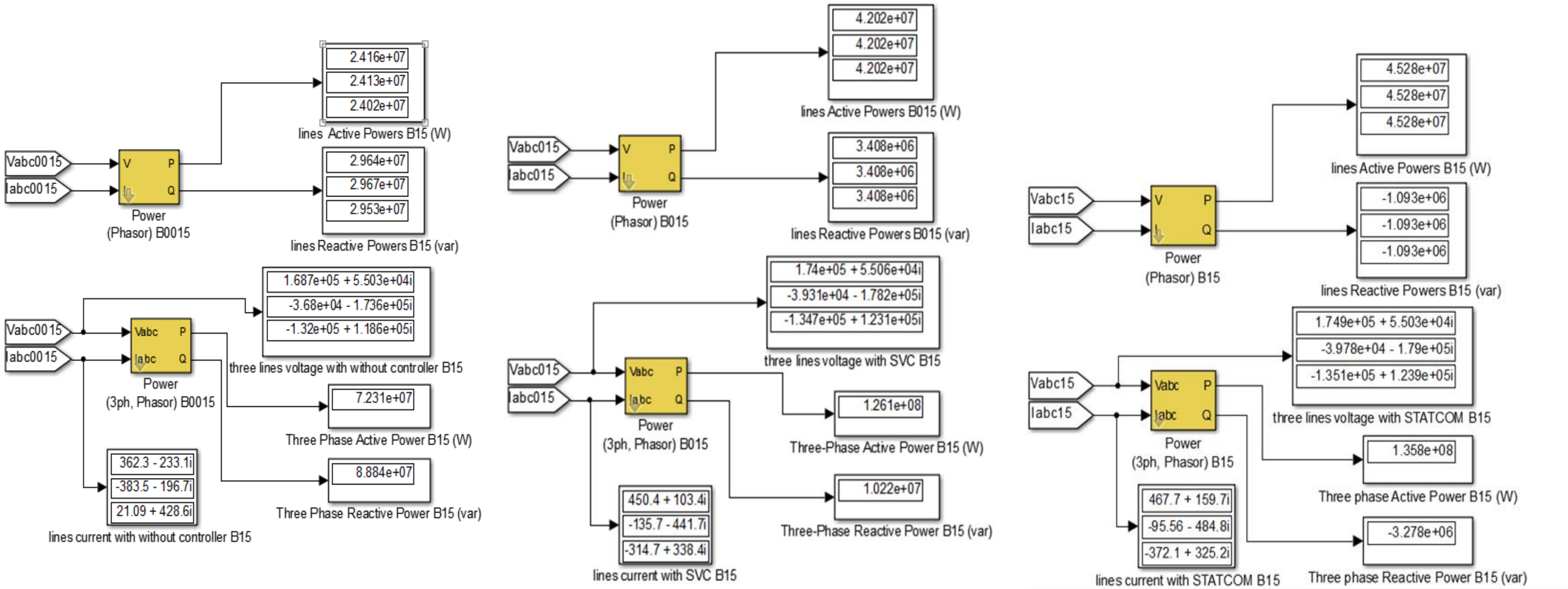


Figure 4.15. Power, current and voltage at B15 with and without a controller.

We can observe that active power transfer, voltage bus, and current is increased when shunt FACTS controllers are connected, and STATCOM is better than SVC for above goal when STATCOM and SVC have the same parameters showed in Case 4.2.1.1

Table 4.13 Simulation results with and without controller at B27

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	130.46	0.988	111.5	96.11	530.8
SVC	130.88	0.991	100.6	104.5	522.6
STATCOM	130.96	0.992	98.85	106.1	522.1

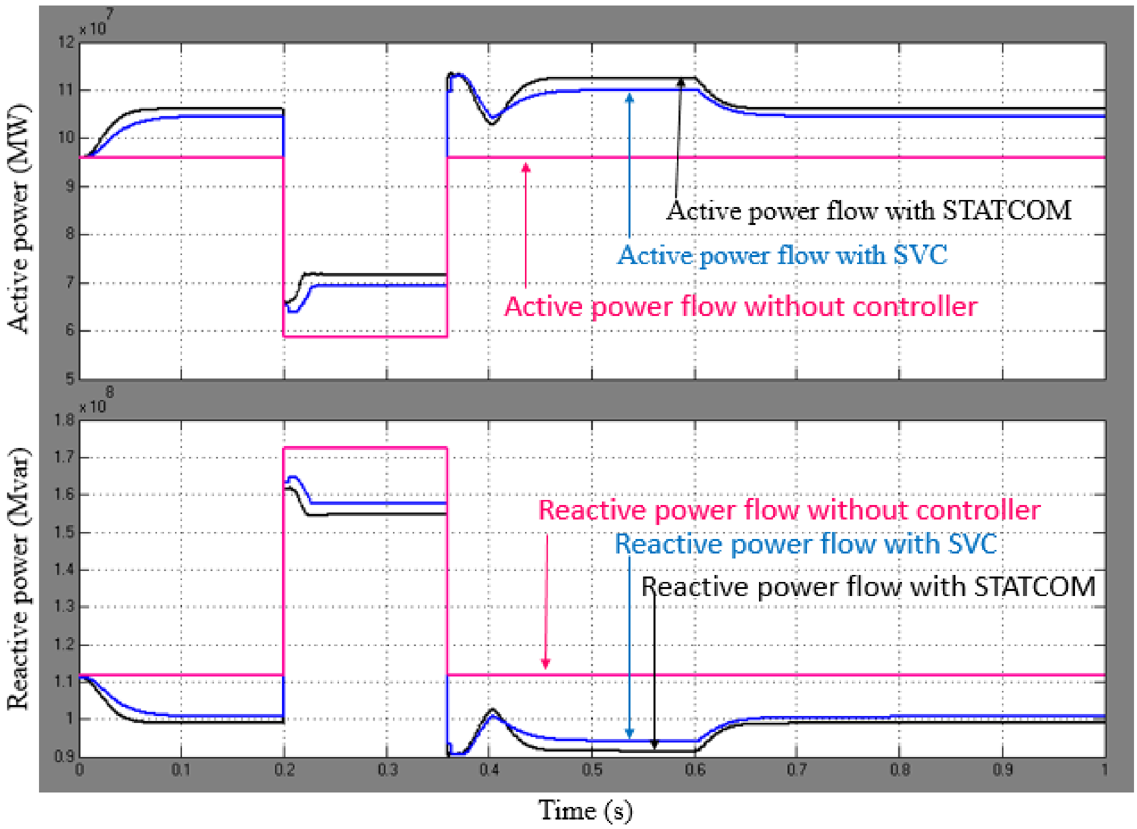


Figure 4.16. Power transfer B27 with and without controller

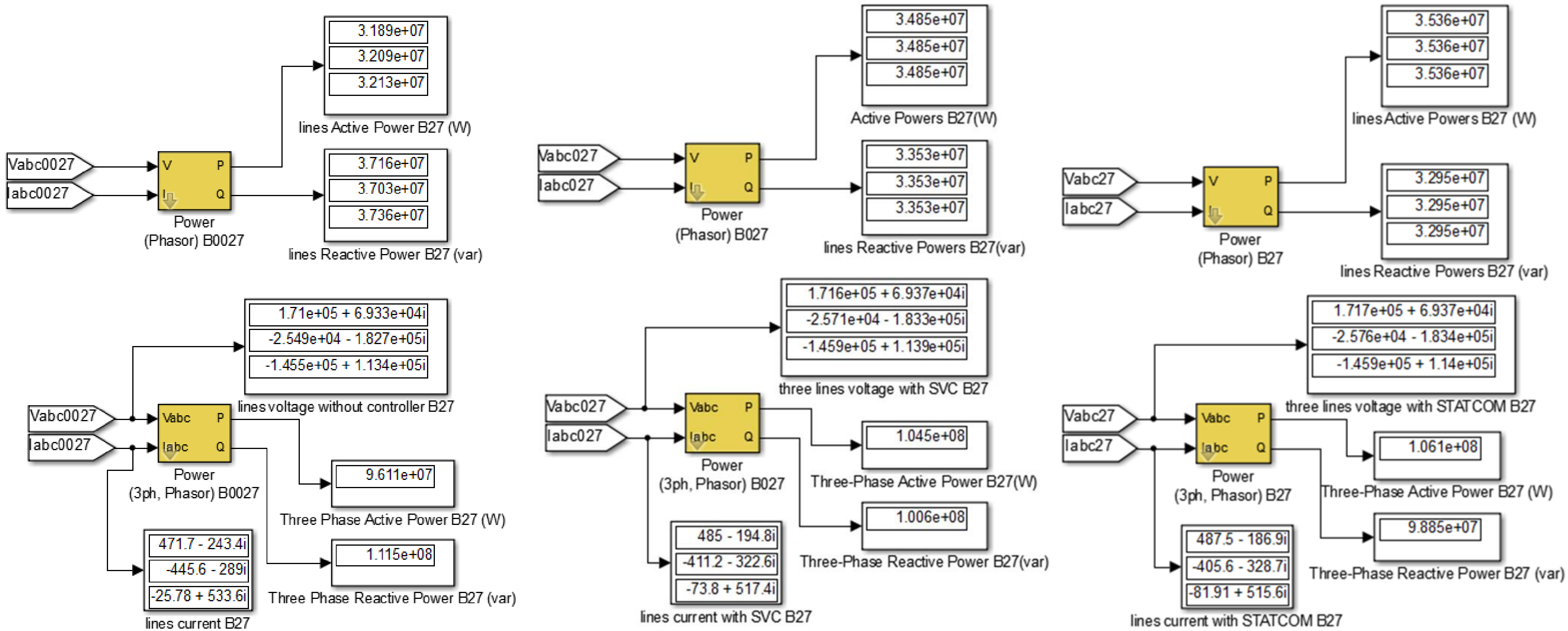


Figure 4.17. Power, current and voltage at B27 with and without a controller.

Table 4.14 Simulation results with and without controller at B34

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	126.36	0.957	39.83	50.52	240.5
SVC	128.76	0.975	14.47	69.94	261.5
STATCOM	129.2	0.979	10.17	73.41	270.4

At B34 the voltage without a controller is 126.36-kilo volt, reactive power flow is 39.83 MVAR, and active power is 50.52 MW. When to connect the shunt FACTS controllers the voltage improved, active power transfer is increase and reactive power transfer decrease. Above results are a goal of this thesis and make the system is more stable. Observed that STATCOM is better than SVC.

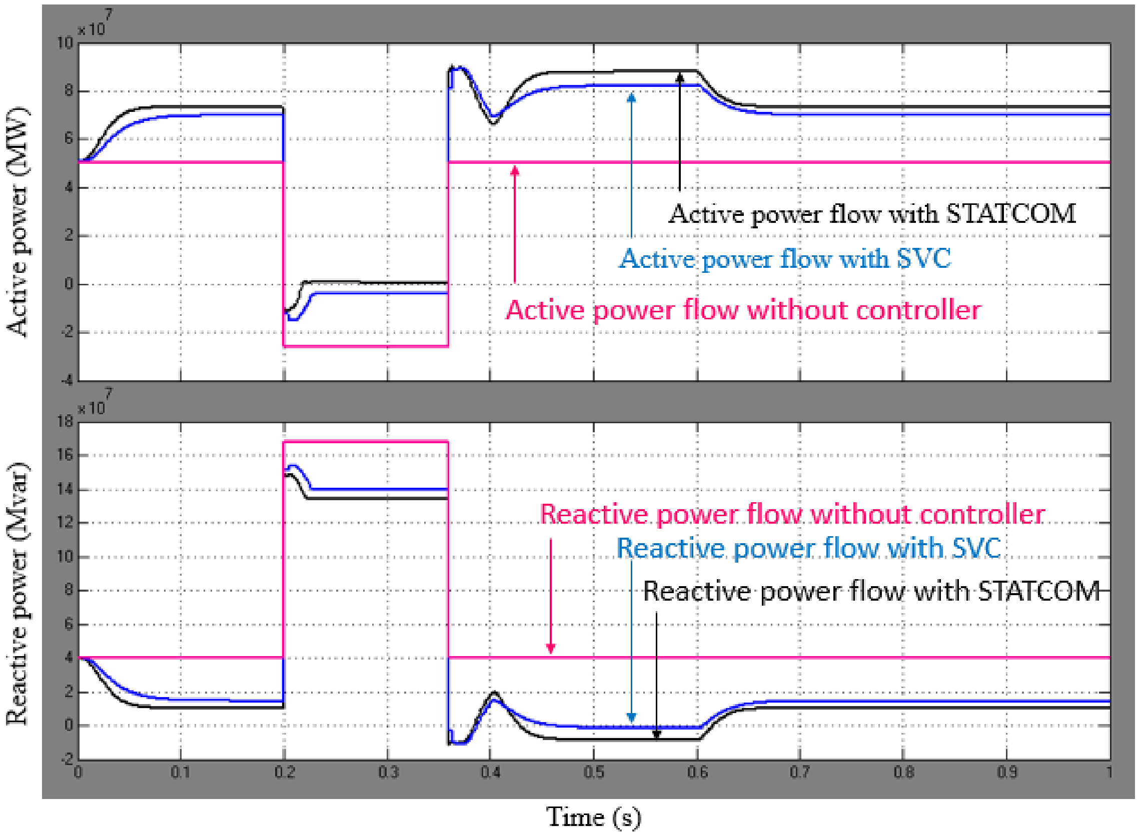


Figure 4.18. Power transfer B34 with and without controller

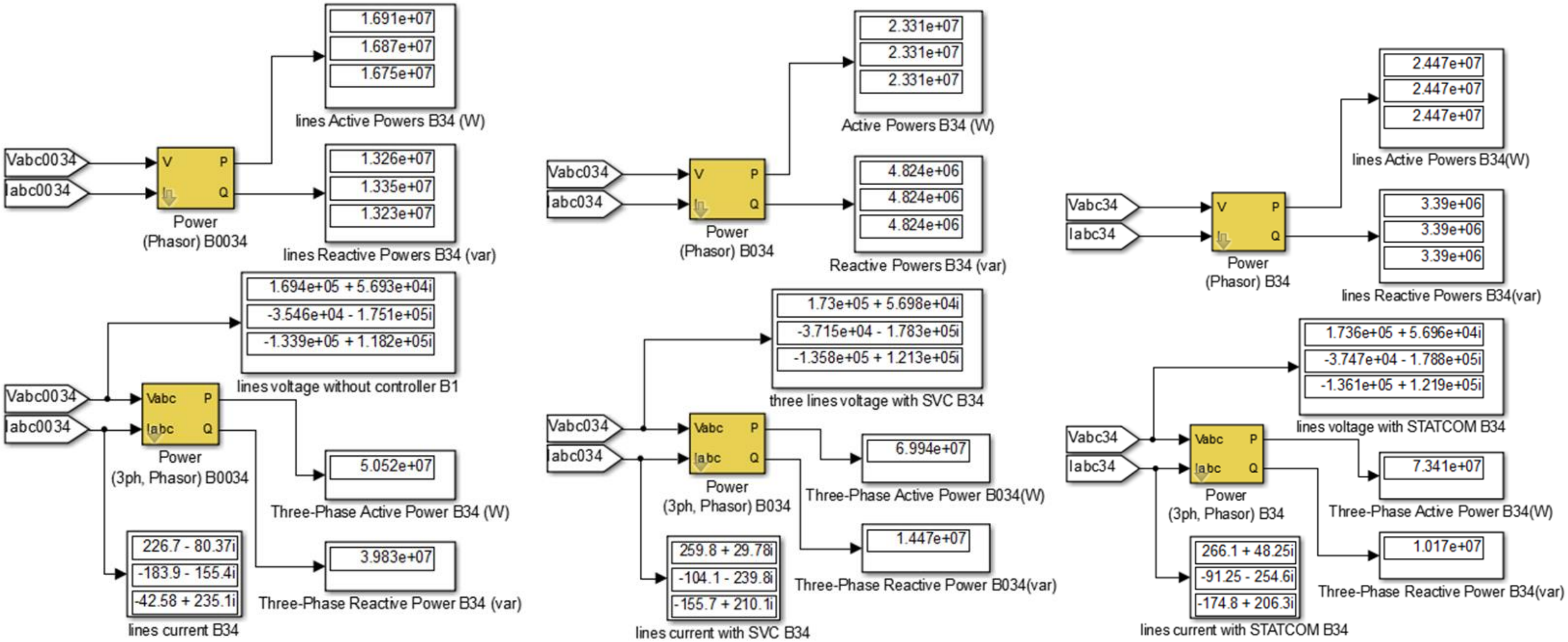


Figure 4.19. Power, current and voltage at B34 with and without a controller.

Table 4.15 Simulation results with and without controller at B24

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	129	0.977	119.4	109.5	568.3
SVC	129.8	0.983	117.5	108.5	580.9
STATCOM	130	0.985	117.1	102.3	581.3

At B24 the voltage without a controller is 129-kilo volt, reactive power flow is 119.4 MVAR, and active power is 109.5 MW. When to connect the shunt FACTS controllers the voltage improved, active power transfer is increase and reactive power transfer decrease. Above results presented a goal of this thesis and made the system is more stable. Observed that STATCOM is better than SVC. Finally, the current with FACTS is an increase. Equation (4.1) is used to proof of guilt that the current is increase with the shunt FACTS.

$$S = \sqrt{3} * V * I \quad \Leftrightarrow \quad S = \sqrt{P^2 + JQ^2} \tag{4.3}$$

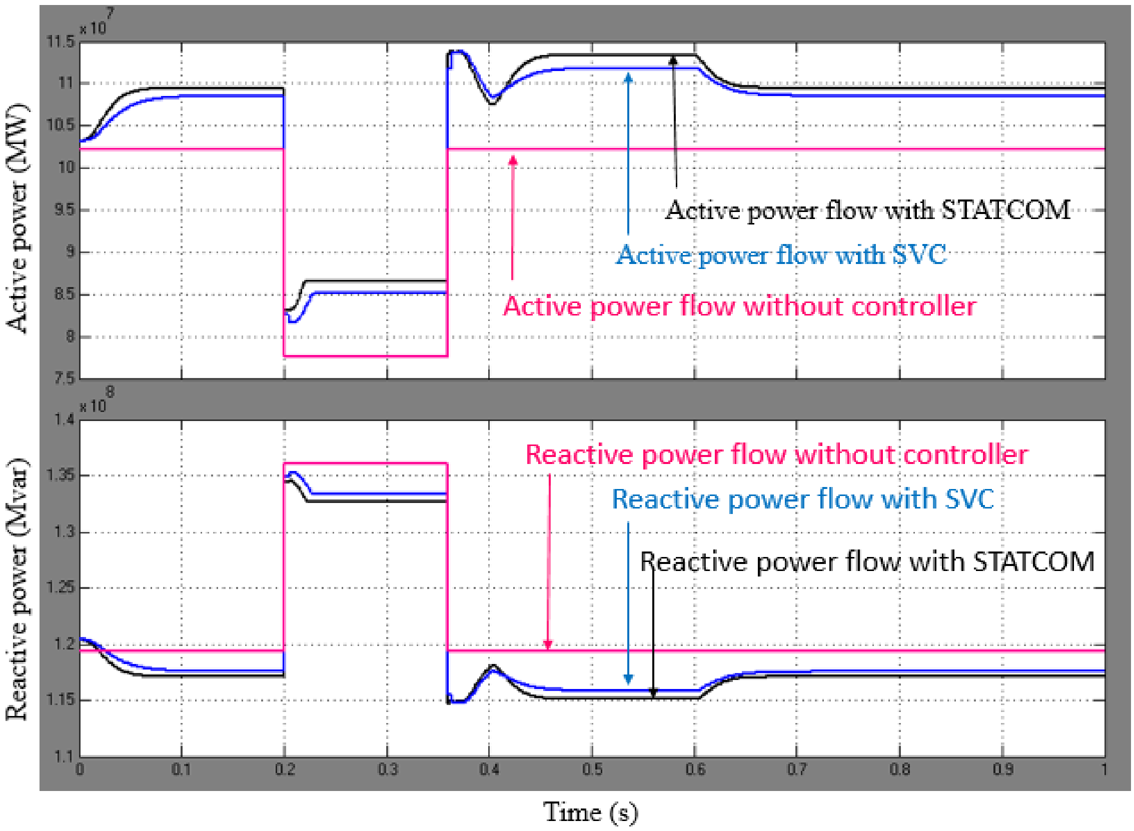


Figure 4.20. Power transfer B24 with and without controller

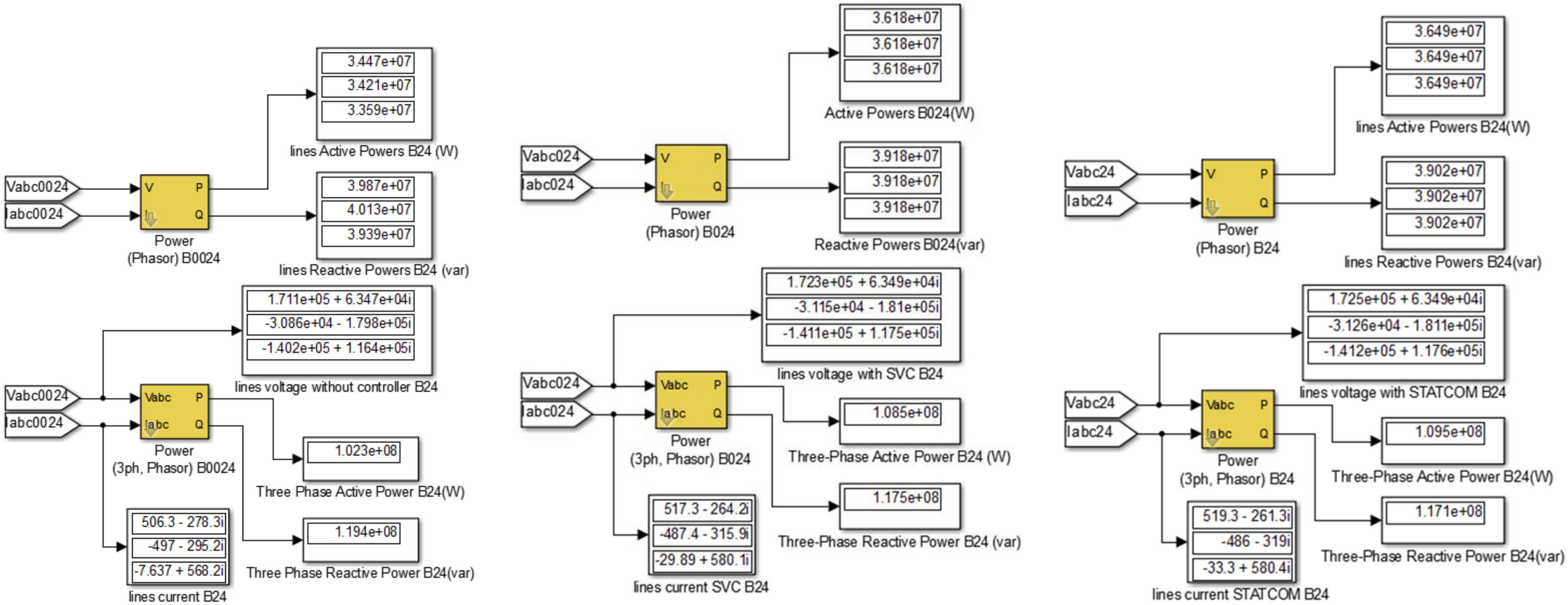


Figure 4.21. Power, current and voltage at B24 with and without a controller.

Table 4.16 Simulation results with and without controller at B16

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	128.2	0.97	78.4	90	432.5
SVC	129.3	0.979	56.26	103.5	429.2
STATCOM	129.55	0.981	52.9	106.3	432.1

At B16 the voltage without a controller is 128.2-kilo volt, reactive power flow is 78.4 MVAR, and active power is 90 MW. When to connect the shunt FACTS controllers the voltage improved, active power transfer is increase and reactive power transfer decrease. Above results goal of this thesis and make the system is more stable. Observed that STATCOM is better than SVC. Finally, the current with FACTS is an increase.

S=√3*V*I and S=√ (P^2) +JQ^2 these two equations are used to prove that the current rise in the shunt FACTS controller.

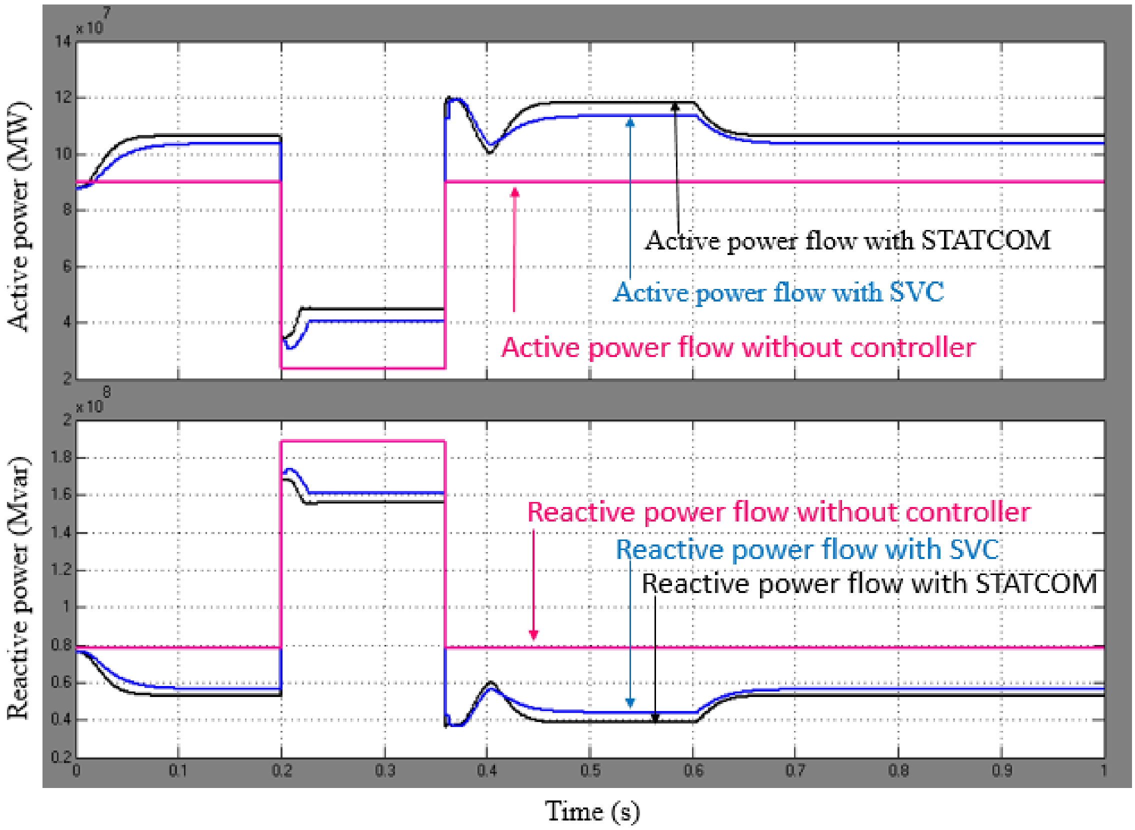


Figure 4.22. Power transfer B16 with and without controller

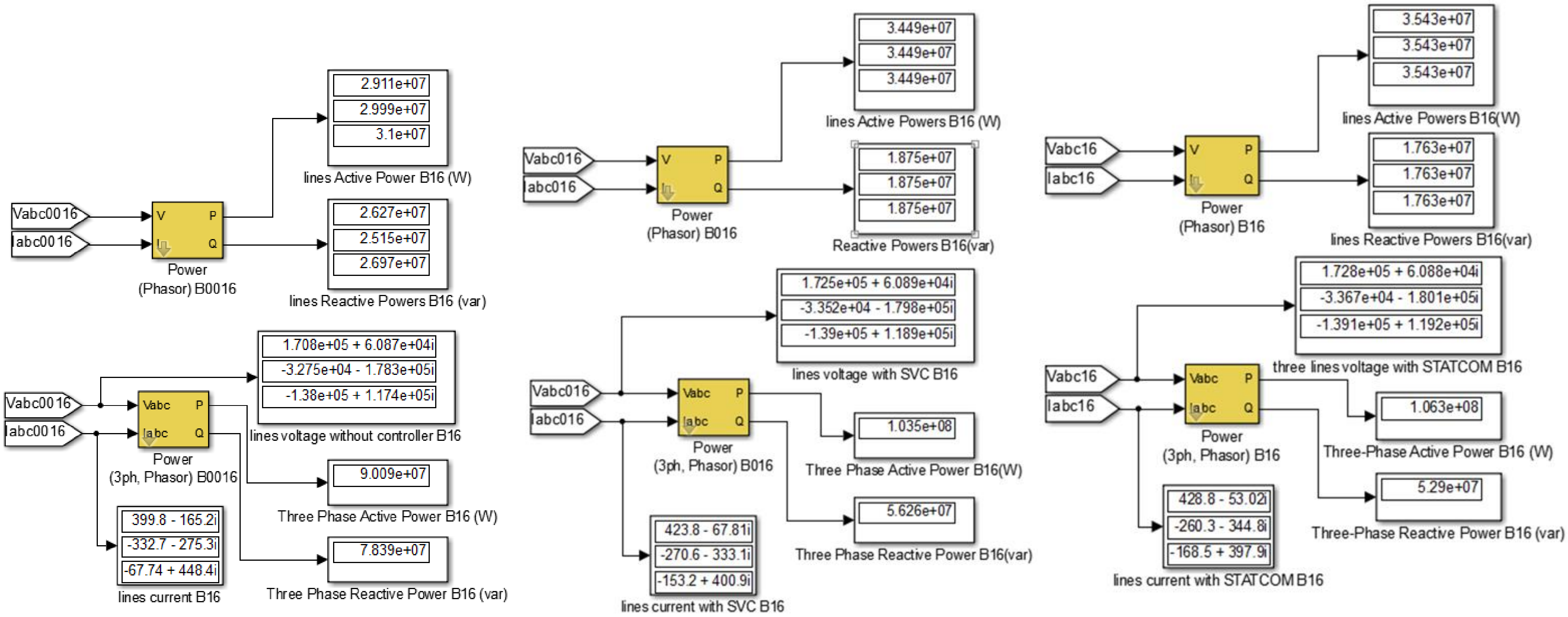


Figure 4.23. Power, current and voltage at B16 with and without a controller.

<u>Case 4.2.1.2</u>: Reactive power limits 146 MVAR and -146 MVAR -Droop =0.03 - Vac regulator gain Kp =5 or 20 and Ki =1000 or 5000 (STATCOM and SVC parameters).in this case active and reactive power transfer don't change only voltage change at transient response that showed at 4.1 voltage response. But when droop is change active, reactive power transfer and voltage is a change that showed in <u>Case 4.2.1.3</u>.

<u>Case 4.2.1.3</u>: Converter rating of STATCOM 146 MVA–Droop (pu) =0.00 - Vac regulator gain Kp =0.5 and Ki =500 and Reactive power limits of SVC 146 MVAR and -146 MVAR. In this case three phase fault occur and time fault is 0.2 to 0.36 second, time simulation 1 second. This case measured power flow and current for five below buses. In this case, we can observe that the power flow with STATCOM and SVC is more controlled.

Table 4.17 Simulation results with and without controller at B15

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	125.5	0.9508	88.84	72.31	429.1
SVC	132	1	-59.43	173.3	654.3
STATCOM	132	1	-59.15	174.6	658.4

Table 4.18 Simulation results with and without controller at B27

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	130.46	0.988	111.5	96.11	530.8
SVC	131.17	0.9937	91.75	112	520.2
STATCOM	131.17	0.9937	91.81	112.2	520.9

Table 4.19 Simulation results with and without controller at B34

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	126.36	0.957	39.83	50.52	240.5
SVC	130.8	0.991	-7.625	86.7	313.7
STATCOM	130.81	0.991	-7.511	87.13	315.2

Table 4.20 Simulation results with and without controller at B24

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	129	0.977	119.4	102.3	568.3
SVC	130.53	0.9888	115.1	113.1	582.9
STATCOM	130.5	0.989	115.2	113.2	583.2

Table 4.21 Simulation results with and without controller at B16

Type of controller	Voltage kV	Voltage pu	Reactive power flow (MVAR)	Active power (MW)	Current (A)
without	128.2	0.97	78.39	90.09	432.5
SVC	130.32	0.987	39.15	117.1	446.7
STATCOM	130.32	0.987	39.25	117.5	448

All above cases, explained the voltage response, current and power flow for five buses in the north of Iraq's power system, when two shunt FACTS devices connect with the 132KV Soran substation. And without controller.

CHAPTER 5

CONCLUSION, SUGGESTION AND FUTURE WORK

5.1. CONCLUSION

Single SVC and STATCOM devices have been added to the network and from results that obtained it can conclude;

1. Adding single SVC and single STATCOM at weakest (Soran) bus in the network will significantly help to improve voltage and operate the network within the allowable range.
2. STATCOM and SVC controllers can be used for reactive power compensation in the north of Iraq’s network and under low voltage conditions.
3. Results show adding SVC and STATCOM devices in the network not improve voltage profile only.
4. Improving system stability by increasing the voltage stability of the system so it increases system security and helps to reduce total blackout of the network.
5. Active power losses in transmission will be decreased. After adding SVC at suggested bus, the active power losses will be decreased by 54MW when compare with the same bus without a controller. Active power generation price is 32$/MWh (Mass Global contract); decrease total estimated cost for one year when SVC is connect = 32 x 24 x 365 x 54 = 15,137,280 $ /year. decrease total estimated cost for one year when STATCOM is connect = 32 x 24 x 365 x 63 = 17,660,160 $ /year
6. Reactive power losses in transmission will be decreased.
7. Transmission line's transmitting capability will be increased.
8. Generation power plants perform better, and their capability of active generation will be better with decreasing reactive power generation.

9. Now in the north of Iraq's power system has shunt capacitors device to voltage control, advantages of shunt capacitors are much lower cost compared to (STATCOMs, SVCs) and switching speeds can be quite fast witted current limiting reactors to minimize switching.
10. STATCOMs, SVCs are more reliable than shunt capacitor reactive power compensator. Because when the voltage system goes to the nose point, SVCs and STATCOMs are generating more reactive power to the system, that's cause to control very low voltage.
11. The STATCOM is more robust and effective than an SVC in providing voltage support and stability improvements.
12. The output current of STATCOM can be controlled up to the rated maximum capacitive or inductive range.
13. The reactive components used in the STATCOM are much smaller than those in the SVC.
14. The STATCOM performs the same function as the SVC. However, at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. This is due to the fact that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage (constant current). This ability to provide more capacitive reactive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibits a faster response than the SVC because with the VSC, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for a SVC).

5.2. SUGGESTION

The suggestions can be summarized as following;

1. Adding SVC and STATCOM devices (146 MVAR) in Erbil Governorate at Soran substation. This step will improve network voltage and decrease the transmission lines losses, thereby sending more active power.
2. Best network voltage level (average = 0.9772 pu) can be achieved by adding one SVC devices at Soran substation and Best network voltage level (average =

0.9818 pu) can be achieved by adding one STATCOM devices at Soran substation. Above results obtain when droops of STATCOM and SVC equal 0.03

3. I have idea about renewing the transmission lines in the north of Iraq's power system and change high voltage level from 132 KV to 500 KV, however, more expensive but at that moment, we can:

- increase active power transfer to the consumers
    - Active Power Flow = Vs * V r / X   (constant X)

- Decrease current absorb by load, thereby reactive power flow play down
    - Power = Voltage * Current
    - Apparent power = Active power + Reactive power

- Decrease transmission line losses
    - Losses = Resistance * (Current) ^2

If we want to transfer 500 MW from generator to consumer

1. At 500 KV, Current absorb is 1000 Amperes
2. At 132 KV, Current absorb is 3787 Amperes

Losses higher when the high voltage system is 132 KV because absorbing 3787 amperes by 500 MW. But when to increase high voltage level to 500 KV current absorb by the same load (500 MW) reduce to 1000 amperes using that transmission line losses decrease.

Figure 5.1 Distribution voltage drop over insulator 11kv

5.3. FUTURE WORK

1. In this thesis, improving static voltage of the north of Iraq's power network during and after fault clearance and could improve the transfer capacity by using SVC and STATCOM controllers. Future work can involve using multi-level SVC and STATCOM to reduce the harmonics of the system. Also, using three types of STATCOM and SVC controller such as PID, PI, and Fuzzy logic controller.

2. The STATCOM and SVC controller parameters are selected by trial and error method in this thesis. Rigorous control design techniques may be utilized for determining optimal controllers to achieve an even better response of STATCOM and SVC.

3. In this thesis, generators are considered as voltage sources without exciter and automatic voltage regulator. It is possible that other FACTS devices and generator excitation systems are electrically close to the STATCOM bus. Hence, a coordinated control of the STATCOM with other controls present nearby may be studied before their implementation.

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APPENDIX X

Active and Reactive load in the north of Iraq's Substations

No.	Slymaniah Substations Name	NO. of Buses	Active load (MW)	Reactive load (Mvar)
1	**KALAR** + Kulajo,10MVA	B3	92+4=96	7+1=8
2	**derbendexan**	B2	43	19
3	**TANJARO**	B6	3	1
4	**S.SADIQ+** S.S.-M 25MVA	B5	52+0=52	25+0=25
5	**BAKRAJO+** Bkrajo-M 25MVA+ Bazyan Cement Fac.63 MVA+ GRD(Delta)Fac.	B8	30+4.5+15+22= 71.5	17+2.1+4+5=28.1
6	**KIFRI**	B4		
7	**CHAMCHAMAL+** Chamchamal-M 15MVA+ MASS STEEL FAC.	B33	41+0+28 =69	19+0+8.9 =27.9
8	**BARDAQARAMAN**	B29	4.7	1.7
9	**REZGARI**	B9	69	21
10	**SOUTH SULY+** Kaziwa,25MVA	B7	78+10.7 =88.7	25+4.25 =29.25
11	**Penjuen**		New S.S	Until Now with S.Sadiq B5
12	**Halabja Shahid**		New S.S	Until Now with S.Sadiq B5
13	**AZMAR+** Hawarishar,25MVA+ Chwarta (Sharbazher)	B10	40+9+0=49	-3+4=1
14	**ZARGATA+** Sherkuzh,15MVA	B11	48+7.3 =55.3	20+2.6=22.6
15	**TASLUJA+** Tasluja-M 15MVA+ SUPER STEEL 63MVA+ MASS CEMENT FAC	B27	44+0+7+33=84	23+0+2+11 =36

16	**DOKANABB**	**B19**	**75**	**32.5**
17	**CHWARQURNA+**Shekarta,25 MVA mobile	**B14**	**62+9=71**	**28+6=34**
18	**RANYA**	**B13**	**34**	**9**
19	**QALADZA**	**B12**	**18**	**-4**
20	**QULARAICY+** Azmer Steel Fac.31.5MVA+ Takia, (1x10+1x15)MVA	**B28**	**1.75+1+8.7=11.45**	**0.78+0+3.4 =4.18**
21	Shekarta,25MVA mobile		**9**	**6**
22	Hawarishar,25MVA		**9**	**4**
23	Tasluja-M 15MVA		**0**	**0**
24	SUPER STEEL 63MVA		**7**	**2**
25	MASS CEMENT FAC.		**33**	**11**
26	Sherkuzh,15MVA		**7.3**	**2.6**
27	Chwarta (Sharbazher)		**0**	**0**
28	Kaziwa,25MVA		**10.7**	**4.25**
29	Azmer Steel Fac.31.5MVA		**1**	**0**
30	Takia, (1x10+1x15)MVA		**8.7**	**3.4**
31	Bkrajo-M 25MVA		**4.5**	**2.1**
32	MASS STEEL FAC.		**28**	**8.9**
33	Chamchamal-M 15MVA		**0**	**0**
34	Kulajo,10MVA		**4**	**1**
35	S.S.-M 25MVA		**0**	**0**
36	Bazyan Cement Fac.63 MVA		**15**	**4**
37	GRD(Delta)Fac.		**22**	**5**
	Erbil .Substation Name		**Active load (MW)**	**Reactive load (Mvar)**
38	**SORAN+** Rawanduz 25MVA mobile+ Khalifan 25MVA+ Spelk 25MVA+ Harir,25MVA	**B15**	**39.6+8.35+7.4+8 +15.15=78.5**	**8+2.6+2.1+3+5.95 =21.65**
39	**SALAHADDIN+** Basrma 25MVA+ Sork, 25MVA+ Malaomar,25MVA	**B34**	**42+0+0+9.5=51.5**	**13+0+0+3.6=16.6**
40	**SHAQLAWA**	**B35**	**2.1**	**0.9**
41	**PIRZIN+** Safin, 25MVA+ Bahrka, 25MVA+ Tarjan,25MVA+ Qarachukh 25MVA+ Shamamk 25MVA	**B23**	**73+12.9+13.1+0 +14.43+12 =125.43**	**7+5.9+4.5+0+4.43 +7 =28.83**
42	**NORTH ERBIL+** Hiwa, 25MVA	**B16**	**51+11.8 =62.8**	**10+4.4=14.4**

43	**PARK+** Lajan 25MVA	**B30**	**105+7=112**	**33+2.5=35.5**
44	**AZADI+** Azadi 25MVA+ Neshtiman, 25MVA	**B22**	**79+12+0 =91**	**41+4+0=45**
45	**NEW KOYA+** Koya-M25MVA	**B17**	**4.7+13 =17.7**	**1.7+7=2.4**
46	**KOYA+** Taqtaq, 25MVA	**B20**	**21+0=21**	**2+0=2**
47	**WEST ERBIL+** Turaq 25MVA+ Chalook 25MVA	**B24**	**62+11.35+12.5= 85.85**	**9+4.25+6.4 =19.65**
48	**KHABAT (KAWRGOSK)+** Ashte,25MVA	**B49**	**95+8=103**	**27+2=29**
49	**SOUTH ERBIL+** Baxamre,25MVA+ Qushtapa+ POLTEKS STEEL FACTORY	**B25**	**60+0+28+0=88**	**17+0+19.4+0=36.4**
50	**NEW ERBIL+** Karezan, 25MVA + Hamren, 25MVA+ Kasnazan, 25MVA	**B21**	**43+10.4+11.6+12.7 =77.7**	**16+3.6+4.65+2.85 =27.1**
51	**EAST ERBIL+** Qalat, 25MVA	**B26**	**87+9.1 =96.1**	**16+10=26**
52	Qushtapa		**28**	**19.4**
53	POLTEKS STEEL FACTORY		**0**	**0**
54	Rawanduz 25MVA mobile		**8.35**	**2.6**
55	Khalifan 25MVA		**7.4**	**2.1**
56	Spelk 25MVA		**8**	**3**
57	Basrma 25MVA		**0**	**0**
58	Sork, 25MVA		**0**	**0**
59	Malaomar,25MVA		**9.5**	**3.6**
60	Safin, 25MVA		**12.9**	**5.9**
61	Bahrka, 25MVA		**13.1**	**4.5**
62	Harir,25MVA		**15.15**	**5.95**
63	Lajan 25MVA		**7**	**2.5**
64	Tarjan,25MVA		**0**	**0**
65	Ashte,25MVA		**8**	**2**
66	Chalook 25MVA		**12.5**	**6.4**
67	Turaq 25MVA		**11.35**	**4.25**
68	Azadi 25MVA		**12**	**4**
69	Karezan, 25MVA		**10.4**	**3.6**
70	Hamren, 25MVA		**11.6**	**4.65**
71	Baxamre,25MVA		**0**	**0**
72	Qalat, 25MVA		**9.1**	**10**
73	Kasnazan, 25MVA		**12.7**	**2.85**

74	Neshtiman, 25MVA		**0**	**0**
75	Hiwa, 25MVA		**11.8**	**4.4**
76	Koya-M25MVA		**13**	**7**
77	Taqtaq, 25MVA		**0**	**0**
78	Qarachukh 25MVA		**14.43**	**4.43**
79	Shamamk 25MVA		**12**	**7**
	Duhok .Substation Name		**Active load (MW)**	**Reactive load (Mvar)**
80	**SARSANG**	**B39**	**31**	**7**
81	**SHAKHKE**	**B38**		
82	**NORTH DUHOK**	**B42**	**22**	**7**
83	**TANAHI**	**B44**	**62**	**21**
84	**EASTDUHOK**	**B45**	**34**	**15**
85	**SUMAIL**	**B37**	**58**	**19**
86	**ZAKHO+** Zakho University 25MVA+ Shahidan ,(2X25)MVA	**B18**	**85+0+9=94**	**35+0+3=38**
87	**WESTDUHOK+** Qasar(Malta), 25MVA	**B41**	**23+7=30**	**8+2=10**
88	**AKRE+** Qasrok 15MVA+ Nahadra, 25MVA+ Mahat 1,25MVA+ Mahat2, 25MVA	**B48**	**39+10+11+8+0= 68**	**20+3+3.3+2.5+0= 28.8**
89	**ZANGANAN+** Bsheryan, 25MVA	**B46**	**24+10=34**	**5+2.9=7.9**
90	**KALAKCHI**	**B43**	**31**	**13**
91	**Fayda+** Alqush, 25MVA+ Khatir, 25MVA	**B40**	**33+9+11 =53**	**15+2+3.1 =20.1**
92	Zakho University 25MVA		**0**	**0**
93	Qasar(Malta), 25MVA		**7**	**2**
94	Qasrok 15MVA		**10**	**3**
95	Nahadra, 25MVA		**11**	**3.3**
96	Mahat 1,25MVA		**8**	**2.5**
97	Mahat2, 25MVA		**0**	**0**
98	Alqush, 25MVA		**9**	**2**
99	Bsheryan, 25MVA		**10**	**2.9**
10	Shahidan ,(2X25)MVA		**9**	**3**
101	Khatir, 25MVA		**11**	**3.1**

Appendix y

Transmission line parameters

Typical 132kV OHL Double Circuit 2xTeal

Electrical Parameters R, X, B (per km)

132KV DC LINE - TWIN TEAL

ACSR "TEAL" PHASE CONDUCTOR + OPGW EATRH WIRE

NUMBER OF CIRCUITS = 2

NUMBER OF EARTH WIRES = 1

FREQUENCY = 50.00 HERTZ

EARTH RESISTIVITY = 1000.0 OHM METRE

LOWEST MIDSPAN HEIGHT = 7.600 METRE

BUNDLE HOR VER

COND DIA R NO SPACING STRANDING CO-ORD CO-ORD

NO MM OHM/KM MM FACTOR METRE METRE

1 25.24 0.1120 2 400.00 0.8228 -3.81 26.750

2 25.24 0.1120 2 400.00 0.8228 -5.22 22.250

3 25.24 0.1120 2 400.00 0.8228 -4.41 17.750

4 25.24 0.1120 2 400.00 0.8228 3.81 26.750

5 25.24 0.1120 2 400.00 0.8228 5.22 22.250

6 25.24 0.1120 2 400.00 0.8228 4.41 17.750

7 15.00 0.5000 1 0.00 0.7250 0.00 33.620

R X B

OHM/KM OHM/KM MICRO-SIEMENS/KM

CIRCUIT 1

POS SEQ 0.056312 0.282197 4.067228

ZERO SEQ 0.314472 1.104250 2.228646

CIRCUIT 2

POS SEQ 0.056312 0.282197 4.067228

ZERO SEQ 0.314472 1.104250 2.228646

MUTUAL

ZERO SEQ 0.258469 0.714909 0.716381

Typical Line Parameters for 132kV DC OHL – 2 LARK conductors / phase

132KV DC LINE - TWIN LARK

2xACSR "LARK" - 1x OPGW

NUMBER OF CIRCUITS = 2

NUMBER OF EARTH WIRES = 1

FREQUENCY = 50.00 HERTZ

EARTH RESISTIVITY = 1000.0 OHM METRE

LOWEST MIDSPAN HEIGHT = 7.000 METRE

COND NO	DIA MM	R OHM/KM	BUNDLE NO	BUNDLE SPACING MM	STRANDING FACTOR	HOR CO-ORD METRE	VER CO-ORD METRE
1	20.44	0.1434	2	400.00	0.8228	-4.40	29.750
2	20.44	0.1434	2	400.00	0.8228	-5.73	24.550
3	20.44	0.1434	2	400.00	0.8228	-4.85	20.000
4	20.44	0.1434	2	400.00	0.8228	4.40	29.750
5	20.44	0.1434	2	400.00	0.8228	5.73	24.550
6	20.44	0.1434	2	400.00	0.8228	4.85	20.000
7	15.00	0.5000	1	0.00	0.7250	0.00	38.100

	R OHM/KM	X OHM/KM	B MICRO-SIEMEN/KM
CIRCUIT 1			
POS SEQ	0.071970	0.293532	3.902694
ZERO SEQ	0.321328	1.120333	2.169180
CIRCUIT 2			
POS SEQ	0.071970	0.293532	3.902694
ZERO SEQ	0.321328	1.120333	2.169181

Typical Line Parameters for 132kV DC OHL – 1 TEAL with KEC towers

KEC 132KV DC LINE - TEAL

1xACSR "TEAL" - 1x OPGW

NUMBER OF CIRCUITS = 2

NUMBER OF EARTH WIRES = 1

FREQUENCY = 50.00 HERTZ

EARTH RESISTIVITY = 1000.0 OHM METRE

LOWEST MIDSPAN HEIGHT = 7.000 METRE

COND NO	DIA MM	R OHM/KM	BUNDLE NO	BUNDLE SPACING MM	STRANDING FACTOR	HOR CO-ORD METRE	VER CO-ORD METRE
1	25.24	0.1120	1	0.00	0.8228	-4.00	32.400
2	25.24	0.1120	1	0.00	0.8228	-5.18	27.350
3	25.24	0.1120	1	0.00	0.8228	-4.30	23.000
4	25.24	0.1120	1	0.00	0.8228	4.00	32.400
5	25.24	0.1120	1	0.00	0.8228	5.18	27.350
6	25.24	0.1120	1	0.00	0.8228	4.30	23.000
7	15.00	0.5000	1	0.00	0.7250	0.00	39.740

	R OHM/KM	X OHM/KM	B MICRO-SIEMEN/KM
CIRCUIT 1			
POS SEQ	0.112303	0.399159	2.875613
ZERO SEQ	0.367036	1.221750	1.782966
CIRCUIT 2			
POS SEQ	0.112303	0.399159	2.875613
ZERO SEQ	0.367036	1.221750	1.782966

132KV DC LINE: 1 x HTLS "Wabash" + 1 x OPGW

NUMBER OF CIRCUITS = 2

NUMBER OF EARTH WIRES = 1

FREQUENCY = 50.00 HERTZ

EARTH RESISTIVITY = 1000.0 OHM METRE

LOWEST MIDSPAN HEIGHT = 7.600 METRE

BUNDLE HOR VER

COND DIA R NO SPACING STRANDING CO-ORD CO-ORD

NO MM OHM/KM MM FACTOR METRE METRE

1 25.24 0.1014 1 0.00 0.8228 -3.81 26.750

2 25.24 0.1014 1 0.00 0.8228 -5.22 22.250

3 25.24 0.1014 1 0.00 0.8228 -4.41 17.750

4 25.24 0.1014 1 0.00 0.8228 3.81 26.750

5 25.24 0.1014 1 0.00 0.8228 5.22 22.250

6 25.24 0.1014 1 0.00 0.8228 4.41 17.750

7 15.00 0.5000 1 0.00 0.7250 0.00 33.620

R X B

OHM/KM OHM/KM MICRO-SIEMEN/KM

CIRCUIT 1

POS SEQ 0.101712 0.396904 2.893383

ZERO SEQ 0.359872 1.218957 1.795724

CIRCUIT 2

POS SEQ 0.101712 0.396904 2.893383

ZERO SEQ 0.359872 1.218957 1.795725

MUTUAL

ZERO SEQ 0.258469 0.714909 0.482159

IMPEDANCE

MATRICES SERIES SHUNT

R X Z X

ELEMENT OHM/KM OHM/KM OHM/KM MEGOHM-KM

1 1 0.19550 0.65474 0.68330 -0.440323

1 2 0.08929 0.28018 0.29406 -0.100832

1 3 0.08646 0.24523 0.26003 -0.060267

1 4 0.09410 0.24016 0.25793 -0.074819

1 5 0.08929 0.23239 0.24895 -0.059093

1 6 0.08646 0.22631 0.24227 -0.045027

2 2 0.18635 0.67376 0.69906 -0.436406

2 3 0.08241 0.29665 0.30788 -0.093042

2 4 0.08929 0.23239 0.24895 -0.059093

2 5 0.08495 0.23939 0.25402 -0.055004

2 6 0.08241 0.24364 0.25720 -0.048402

3 3 0.18144 0.68427 0.70791 -0.421525

3 4 0.08646 0.22631 0.24227 -0.045027

3 5 0.08241 0.24364 0.25720 -0.048402

3 6 0.08004 0.26049 0.27251 -0.051056

4 4 0.19550 0.65474 0.68330 -0.440323

4 5 0.08929 0.28018 0.29406 -0.100832

4 6 0.08646 0.24523 0.26003 -0.060267

5 5 0.18635 0.67376 0.69906 -0.436407

5 6 0.08241 0.29665 0.30788 -0.093042

6 6 0.18144 0.68427 0.70791 -0.421525

SERIES SHUNT

ADMITTANCE G B B

MATRICES SIEMEN-KM SIEMEN-KM MICRO-SIEMEN/KM

1 1 0.51033 -1.97792 2.48541

1 2 -0.14019 0.44591 -0.46137

1 3 -0.04928 0.27132 -0.19011

1 4 -0.06615 0.32147 -0.28743

1 5 -0.02916 0.22722 -0.16712

1 6 -0.02104 0.20279 -0.11150

2 2 0.51939 -2.01842 2.54857

2 3 -0.15927 0.46931 -0.44617

2 4 -0.02916 0.22722 -0.16712

2 5 -0.02765 0.20941 -0.14206

2 6 -0.03839 0.22934 -0.13406

3 3 0.47432 -1.94658 2.54851

3 4 -0.02104 0.20279 -0.11150

3 5 -0.03839 0.22934 -0.13406

3 6 -0.08273 0.31296 -0.19161

4 4 0.51033 -1.97792 2.48541

4 5 -0.14019 0.44591 -0.46137

4 6 -0.04928 0.27132 -0.19011

5 5 0.51939 -2.01842 2.54857

5 6 -0.15927 0.46931 -0.44617

5 6 0.47432 -1.94658 2.54851

Appendix z

List of Fixed Capacitor Banks and Buses Number

Bus Number	Bus Name(132/33/11)kv	On service	Capacity (Mvar)
B1	DOK/HPS		
B2	DBK/HPS		
B3	KALAR	2*10	3*10
B4	KIFRI	1*10	2*10
B5	S.SADIQ	4*10	6*10
B6	TANJARO	2*10	2*10
B7	SOUTH.SULY	1*10	3*10
B8	BAKRAJO	1*10	2*10
B9	REZGARI	2*10	6*10
B10	AZMAR	4*10	4*10
B11	ZARGATA		
B12	QALADZA	2*10	2*10
B13	RANYA		2*10
B14	CHWARQURNA	1*10	1*10
B15	SORAN		2*10
B16	NORTH ERBIL	1*10	3*10
B17	NEW KOYA		2*10
B18			
B19	DOKAN		
B20	KOYA	2*10	2*10
B21	NEW ERBIL	3*10	3*10
B22	AZADI		2*10
B23	PERZIN		3*10
B24	WEAST ERBIL	3*10	3*10

B25	SOUTH ERBIL	2*10	6*10
B26	EAST ERBIL	2*10	3*10
B27	TASLUJA	2*10	2*10
B28	QULARAICY	1*10	4*10
B29	BARDAQARAMAN	2*10	2*10
B30	PARK	2*10	3*10
B31	EGPP	4*30	4*30
B32	SGPP		3*30
B33	CHAMCHAMAL	2*10	3*10
B34	SALAHADDIN		2*10
B35	SHAQLAWA		2*10
B36	DGPP		
B37	SUMAIL	2*10	4*10
B38	SHAKHKE	2*10	3*10
B39	SARSNG	1*10	2*10
B40	FAYDA	2*10	2*10
B41	WEAST DUHOK	2*10	3*10
B42	NORTH DUHOK		2*10
B43	KALAKCHI		3*10
B44	TANAHI		3*10
B45	EAST DUHOK	3*10	3*10
B46	ZANGANAN		3*10
B47	DUHOK 29 MW		
B48	AKRE		3*10
B49	KHABAT		2*10
B50	In side DBK/HPS		
B51	In side DHPS		
B52	In side SGPP		
B53	In side EGPP		
B54	In side DGPP		

Appendix A

SVC parameters

SVC parameters power data

System nominal voltage 132 kV

Nominal frequency 50 Hz

Three-phase base power =100 MVA

Reactive power limits 146 MVAR and -146 MVAR

Average time delay due to thyristor valves firing Td = 4e-3 S

SVC parameters / Control parameter/voltage regulation

Reference voltage Vref=1 pu

Droop =0.03 and 0

Vac regulator gain Kp=0.5, 5, 20 and Ki=500, 1000, 5000

SVC parameters / Control parameter/var control

Bref for var control model = 0 pu/pbase

Appendix B

STATCOM parameters

STATCOM parameters power data

System nominal voltage 132 kv

Nominal frequency 50 Hz

Converter rerating 146 MVA

Converter impedance R=0.00733 pu and L=0.22 pu

DC link nominal voltage 40kv

STATCOM parameters / Control parameter/voltage regulation

Maximum rate of change of reference voltage Vref=10 pu/s

Droop =0.03

Vac regulator gain Kp=0.5 and Ki=500

Vdc regulator gain Kp= 0.1e-3 and Ki= 20e-3

Current regulators gain Kp=0.3, Ki=10 and Kf=0.22

C=375 µF

STATCOM parameters / Control parameter/var control

Reactive power set point Qref = 0 pu

Current regulators gain Kp=0.3, Ki=10 and Kf=0.22

Maximum rate of change of Reactive power set point Qref= 2 pu/s

Vdc regulator gain Kp= 0.1e-3 and Ki= 20e-3